

NASA Technical Memorandum 72861

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Dryden Flight Research Center
Edwards, California



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and Space Administration

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INTRODUCTION

In the past 10 years, U.S. military aviation has progressed from the generation of the F-4/F-8 air superiority fighter to that of the F-15/16/18 aircraft, which are demonstrating significant improvements in maneuver performance. These improvements result from more sophisticated aerodynamic design, lower wing loading, and higher thrust-to-weight ratio, and they permit the newer fighters to maneuver as well at 7 to 8 g's as the earlier aircraft did at 4 to 5 g's. The limited assessment to date of the newer fighters indicates that they also track as well at 7 to 8 g's as their predecessors did at 4 to 5 g's. This is attributed largely to their improved aerodynamics and more sophisticated control systems, which permit them to operate at higher load factors with lower levels of buffet intensity and wing rock than their predecessors. The newer fighters are still characterized by some basic handling qualities deficiencies, however, and some of these may be attributed to their high-gain, high-authority augmentation systems.

NASA has supported the development of these aircraft through activities that range from wind-tunnel studies to full-scale flight programs. References 1 and 2 report work that is typical of NASA's efforts in the latter area. This work is continuing, and the present report summarizes data obtained in the course of a flying qualities study of an early prototype F-15 airplane that was conducted at the NASA Dryden Flight Research Center (DFRC) in 1976. References 3 and 4 summarize Air Force Flight Test Center (AFFTC) F-15 flying qualities programs.

Most of the data reported herein were obtained from 10 caged pipper gunsight tracking flights. Reference 5 discusses this flight test technique in some depth. It should be pointed out that this type of tracking is an engineering tool. In no way should it be construed as an accurate measure of the kill probability of the F-15 airplane. The technique does, however, involve a closed-loop, high-gain piloting task that permits a quantitative assessment of the airplane's flying qualities.

SYMBOLS AND ABBREVIATIONS

AFCS	automatic flight control system
ARI	aileron-to-rudder interconnect
a_n	airplane normal acceleration, g
CAS	command augmentation system
C_N	airplane normal-force coefficient, $\frac{W/S \times a_n}{\bar{q}}$
F_p	pedal force, N
F_x	longitudinal stick force, N
F_y	lateral stick force, N
h_p	pressure altitude, m
M	Mach number
PRAD	pitch ratio adjust device
PTC	pitch trim compensator
p	rolling angular velocity, deg/sec
q	pitching angular velocity, deg/sec
\bar{q}	dynamic pressure, kN/m ²
RRAD	roll ratio adjust device
r	yawing angular velocity, deg/sec
S	wing area, m ²
t	time, sec
W	airplane weight, kN
α	airplane angle of attack, deg
β	airplane angle of sideslip, deg

δ_a	aileron deflection, deg
δ_d	differential stabilator deflection, deg
δ_e	collective stabilator deflection, deg
δ_r	rudder deflection, deg
δ_{stk}	lateral stick deflection, m
ε	rms tracking error, mil
$\bar{\sigma}$	rms normalized buffet intensity, g

Subscripts:

A	azimuth (tracking error)
ckpt	cockpit
init	initial
max	maximum
P	pitch (tracking error)
R	radial (tracking error)
WT	wingtip

INSTRUMENTATION AND DATA REDUCTION

The test airplane was equipped with a complete set of airplane response instrumentation and included a gunsight and gun camera. All the data presented in this report were derived from the eight-bit data acquisition system installed by the airplane manufacturer. This system was maintained by NASA technicians, and the data reduction was generated by the DFRC computing facility. The gun camera film was scored by the AFFTC Data Operations Division, and the tracking error computations were performed by the DFRC computing facility.

DATA ANALYSIS

Gunsight Tracking

The gunsight tracking maneuver was a windup turn from 1 g trim to the maximum allowable load factor or angle of attack. The gun camera film was scored from the first readable frame after the pilot engaged the gunsight trigger to the last readable frame of each run. On occasion, the last readable frame was not the maximum load factor or angle of attack attained in that particular run because gunsight jitter or ground clutter made accurate scoring impossible. The film was scored on a film reader that tabulated both pitch and azimuth or yaw errors at a rate of eight times per second. A tracking error card deck was then run through a computer program that computed pitch, azimuth, and radial rms tracking error in mils for the entire run. The tracking film was time correlated with the onboard instrumentation through an event marker system. Additional information concerning the tracking maneuver and scoring procedures may be found in reference 5.

Buffet

Fluctuating loads from wingtip and pilot station accelerometers were analyzed for continuous 1-second time segments during periods of increasing angle of attack. Computer programs were used to separate the oscillating loads from the maneuver loads and to extract the rms value of the oscillating loads for each selected time segment. These values, normalized to a constant value of dynamic pressure, were defined as buffet loads. Buffet intensity rise was defined as the point at which the buffet load increased rapidly—the knee of the C_N versus $\bar{\sigma}$ curve.

Wing Rock

Wing rock, defined for DFRC studies as an irregular, uncommanded, and uncontrollable roll/yaw oscillation, is associated with wing flow separation and generally occurs at a lift coefficient slightly higher than that for buffet intensity rise. The degradation in precision controllability in the presence of wing rock is largely a function of the degree of aerodynamic and control system coupling and therefore varies from airplane to airplane. Past studies have shown that tracking errors become significant when roll rates exceed approximately ± 10 degrees per second. The wing rock onset boundary for DFRC gunsight tracking studies is obtained from smooth windup turn maneuvers at the angle of attack where the first significant uncommanded roll rate excursion is detected.

AIRPLANE DESCRIPTION

The F-15 airplane is a single-place, supersonic, long-range, all-weather air superiority fighter built by the McDonnell Douglas Aircraft Corporation. Thrust is provided by two Pratt & Whitney F100-PW-100 turbofan engines with variable

afterburning thrust. Gross takeoff weight is approximately 180 kilonewtons. The airplane is characterized by a shoulder-mounted swept wing with twin horizontal ramp inlets and twin vertical stabilizers (fig. 1). The wing, which was designed primarily for transonic maneuverability, has no active maneuver enhancement devices. Some of the F-15 airplane's dimensions are listed in table 1.

The test vehicle (F-15 number 8) was formerly used as the spin research airplane and had a preproduction control system and an externally mounted spin recovery chute. The wingtips were raked as in the production configuration. The modifications made to prepare the airplane for the subject study were to remove the spin chute cannister (leaving the chute housing, however), rework the electrical system until it matched the production configuration, and reballast the airplane. Further, since the aileron-to-rudder interconnect (ARI) gain was scheduled as a function of horizontal stabilator position, the stabilator was rerigged to account for the pitching-moment effects of the loss of the spin chute cannister.

Because of adverse pilot comments concerning the airplane's handling qualities during early tracking tests, the preproduction control system was upgraded to meet production standards with regard to friction, hysteresis, and breakout forces; the spin chute housing was removed and the aft fuselage section was reconfigured to match the production configuration; the roll and trim actuators were replaced, and the ARI was replaced with a production unit; and the stick grip was shimmed to reduce free play. The last four tracking flights were performed after these modifications, which upgraded the airplane to production status.

A detailed control system description is given in reference 3; however, an abbreviated description is presented in the appendix to give an understanding of those features that are believed to have affected pilot opinion during the DFRC precision controllability study.

TEST PROGRAM

Ten caged pipper windup turn tracking flights were conducted with a preproduction F-15 airplane by two DFRC pilots with the gunsight pipper in the caged mode and depressed 70 mils. The fixed-reticle or caged pipper mode was selected to keep the problem free of gunsight dynamics and to expedite the engineering analysis. Unfortunately, this mode of operation produces a pendulum effect that is particularly noticeable in airplanes that have significant amounts of adverse aileron yaw. It is necessary to depress the caged pipper to permit the tracking airplane to fly above the target jet wake at the beginning of the run. Since the windup turn tracking maneuvers in the DFRC program were scheduled to reach normal forces of 7 g's, the pipper was depressed 70 mils (the depression angle for approximately 3.5 g's) to minimize this pendulum effect. While pendulum effect does degrade tracking precision somewhat, it does not invalidate the engineering results of the precision controllability studies, since the depression angle is not changed during the program. All published tracking data of this type (the data in refs. 1, 4, and 6, for example), were obtained from caged pipper tracking runs. The target aircraft used for this program were the F-104, T-38, and F-15 airplanes.

The flight regimes of interest (fig. 2) were Mach 0.7 at an altitude of 6000 meters, Mach 0.9 at 3000 meters, and Mach 0.9 at 10,000 meters. Although no great effort was made to repeat these flight conditions exactly (Earlier studies had shown this to be unimportant), an attempt was made to cover as wide an angle of attack range at each flight condition as practicable to investigate the effects of wing rock on tracking. The normal load factor/angle of attack envelope covered in this program is presented in figure 3. The angles of attack for wing rock onset for the flight conditions of interest are also noted in the figure. Both figures 2 and 3 differentiate between the data acquired from tracking runs that were conducted before and after the control system was upgraded. Data for one of the four flights (nine runs) conducted after the control system was upgraded do not appear in the figures because of the failure in the onboard tape recording system. Although the failure precluded the acquisition of airplane response data, the tracking runs for the flight were scored and were found to present the same error spread as the other three flights. The errors for this flight are not presented.

RESULTS AND DISCUSSION

Aerodynamic Performance

Buffet intensities at the tracking flight conditions were evaluated by using wingtip accelerations as a measure of airplane buffet and cockpit accelerations and the qualitative assessments of the pilots as indications of buffet at the pilot's station. Figure 4 presents the variation of airplane normal-force coefficient with angle of attack and buffet intensity at the wingtip and the pilot's station. The data were obtained from windup turn maneuvers and, even though thrust was varied to maintain constant Mach number, there was some speed loss near the end of each run, as noted in the C_N versus α plot. Wing buffet, normalized to a constant dynamic pressure, is more severe than in other fighter aircraft evaluated by DFRC. The wing buffet intensity rise is abrupt and occurs at a relatively low angle of attack in the transonic speed range, and the maximum buffet intensity level is quite high (5 to 6 g's rms). The cockpit accelerometer (which was mounted on the pilot's seat rail) shows a relatively high level of vibration (0.1 g rms) before buffet intensity rise and increases to approximately 0.3 g rms at maximum values of airplane normal-force coefficient. Reference 2 shows the cockpit buffet intensity levels for the YF-16 and YF-17 aircraft to be considerably lower than for the F-15 airplane. Recent studies (ref. 6 and others) have pointed out that frequency content is as important to pilot comfort as intensity level, and that the frequencies from 4 to 8 hertz are the most uncomfortable. Limited power spectral density analyses indicate that the significant power for F-15 cockpit buffet lies in the range from 3 to 4 hertz. The physiological studies referred to above indicate that the frequency content of this vibration, coupled with the high steady-state load factors attained during the tracking maneuvers, can both degrade the pilot's tracking performance and lead to pilot fatigue.

The F-15 airplane undergoes mild to moderate wing rock at angles of attack above those for buffet intensity rise throughout the Mach number range tested. With a roll rate of ± 10 degrees per second as the criterion (see DATA ANALYSIS), wing rock onset for the F-15 airplane occurred at angles of attack that varied from

11° to 9° as Mach number increased from 0.70 to 0.90. These angles of attack are 5° to 8° lower than those reported in reference 7, but reference 7 defined wing rock as a larger amplitude, lower frequency, undamped Dutch roll oscillation in which precision controllability would be impossible.

Precision Controllability

General tracking results.—All the tracking data are shown in figure 5 in terms of pitch, azimuth, and radial miss distance as a function of the maximum normal load factor attained in each run. Figure 5(a) shows data from the first tracking runs, and figure 5(b) presents data from runs conducted after the control system was upgraded.

Figure 5 reveals several interesting facets of F-15 precision controllability. First, the radial tracking precision varied from approximately 6 to 20 mils over the load factor range from 2.5 to 8.0 g's. The relatively large error at the lower load factors is attributed to a low-amplitude, high-frequency pitch oscillation coupled with a lateral-directional sluggishness that is caused, at least in part, by adverse aileron yaw and large rudder hysteresis. The hysteresis prevented the ARI from applying enough rudder to overcome the adverse aileron yaw and aggravated the pendulum effect produced by the depressed gunsight pitter. The lateral-directional sluggishness would be ameliorated somewhat by a computing gunsight and possibly a revised ARI schedule.

Second, the pitch axis showed lower miss distances and generally more consistent tracking than the azimuth axis. The pilots were asked not to make rudder pedal inputs during most of the runs, but when they did only small improvements in tracking accuracy resulted. The large directional control system breakout force and hysteresis are believed to be responsible for the lack of significant improvement. Only one run (indicated by the flagged symbols in fig. 5(a)) was made with the command augmentation system (CAS) off. From this run, it appears that turning the CAS off does not affect pitch axis tracking but degrades the azimuth tracking capability. The effects of CAS on tracking precision were pronounced and are discussed in greater depth in the next section.

A comparison of the data in figure 5(b) with the data in figure 5(a) shows that tracking precision was essentially the same before and after the control system was upgraded. Because of the scatter in both sets of data, least-squares slopes are shown for the radial tracking errors to aid in the comparison. The least-squares fairing emphasizes the characteristic increase in radial tracking error with increasing normal load factor and shows the nearly identical slopes and intercepts in figures 5(a) and 5(b).

Unfortunately, time did not permit a detailed assessment to be made of the effects on tracking precision of changes in individual control system components during the control system upgrading. However, the upgrading did not noticeably improve precision controllability. Adverse yaw continued to be a major handling qualities deficiency.

Figure 6 gives additional insight into F-15 handling qualities. It presents the tracking results in figure 5 as a function of the maximum angle of attack

attained in each run. The airplane undergoes mild-to-moderate wing rock at angles of attack above approximately 10° over the entire test Mach number range. Figure 6(a) shows that the overall tracking accuracy for runs that reached angles of attack above wing rock onset was generally no worse than that for runs that remained at lower angles of attack. The consistency is probably contributed to by two factors: (1) the rms error is computed for the entire windup turn tracking run and, in general, tracking in the presence of wing rock for each run is of shorter duration than tracking in the wing-rock-free portion of the run; and (2) the tracking errors at low angles of attack are large as a result of the pendulum effect and adverse control system influences. Wing rock does degrade F-15 tracking precision, however, as is discussed below. The data in figure 6(b), which were acquired after the control system was upgraded, show approximately the same relationships as figure 6(a).

Figure 7 summarizes the radial miss distances for all runs (before and after the control system was upgraded) as a function of Mach number and dynamic pressure. The lower end of the dynamic pressure scale is expanded for clarity. The figure shows a slight increase in tracking error at the higher Mach numbers and dynamic pressures and emphasizes the similarity between the early tracking data and the data obtained after control system upgrading.

Effect of command augmentation system.—All the tracking runs performed with the CAS on were typified by a low-amplitude, high-frequency (approximately 1 Hz) pitch oscillation. This is illustrated in the nearly constant g tracking time history shown in figure 8 for flight at Mach 0.86 and an altitude of 3200 meters with the CAS on. This run was conducted without pilot rudder inputs at an angle of attack well below that for wing rock onset. The pilot is pumping the control stick longitudinally at a rate of 1.2 hertz, an activity that is reflected in the traces for elevator position, pitch rate, normal acceleration, and angle of attack. The effect this pitch sensitivity has on the tracking precision is illustrated in figure 9, which shows the pitch, azimuth, and radial miss distances for the tracking turn in figure 8. The pilot's high-frequency activity must produce some additional tracking error in the pitch axis; more important, it demands a considerable amount of pilot attention that must further degrade overall tracking precision. The rms tracking errors for this run were 6.6 mils, 5.6 mils, and 8.7 mils for the pitch, azimuth, and radial errors, respectively.

Figure 8 also shows that the control stick is being moved laterally at approximately one-half the frequency with which it is being moved longitudinally. A review of roll response (fig. 8) and tracking error (fig. 9) indicates sluggishness in the lateral-directional axis.

The CAS-on gunsight tracking results in references 3 and 4 revealed the same longitudinal and lateral-directional deficiencies. Reference 4 states the two problems to be "(1) a relatively high-frequency (approximately one cycle per second) low-amplitude (approximately ± 3 to 6 mils) longitudinal motion identified as a pitch bobble, and (2) sluggish directional response through the ARI when making lateral stick inputs with feet on the floor." Figure 10, which shows the tracking error for a CAS-on constant g run at Mach 0.80 and an altitude of 6700 meters from reference 4, illustrates these deficiencies and shows a marked similarity to the tracking errors in figure 9. A reference 4 analysis of pitch

sensitivity indicated that it was induced by the pilot through the CAS force characteristics. The two possible causes of the sluggish lateral-directional response suggested by reference 4 are the high hysteresis in the directional control system and the fact that the ARI commands did not provide enough proverse rudder deflection to overcome the hysteresis. Even with rudder pedal inputs, the high breakout forces and hysteresis prevented the use of the rudders from being effective.

With the CAS off, the pitch sensitivity abated somewhat, but lateral stick activity increased considerably. This is apparent in the windup turn tracking time history in figure 11. This run was conducted at the same flight conditions as the time history in figure 8, but for this run, the pilot made rudder inputs in an attempt to improve the coordination of the maneuver. Lateral stick force activity is greater than in figure 8. The pilot's rudder inputs show up in the trace of pedal force, F_p (The rudder position instrumentation was inoperative for this run). The rms tracking errors for this run were 6.0 mils in pitch, 11.2 mils in azimuth, and 12.7 mils in radial error (fig. 12). Compared with the tracking errors shown in figure 9 for a CAS-on run, the pitch tracking error is essentially unchanged, but the azimuth error is larger, causing the radial error to be considerably greater as well. The same results were obtained with the CAS-off constant g tracking run reported in reference 4 and presented in figure 13. The similarity of the azimuth tracking error traces in figures 12 and 13 is marked.

Effect of buffet and wing rock.—The wing buffet of the F-15 airplane is severe at the higher angles of attack, and mild-to-moderate wing rock occurred over the Mach number range of interest at angles of attack above approximately 10° .

The control system of the F-15 airplane affected its tracking precision more than the control systems of previous aircraft studied at DFRC. Control system effects were particularly pronounced at the lower angles of attack (normal load factors), where it was difficult to separate the effects of buffet from those of the control system. However, there was a degradation in tracking precision with increasing angle of attack once buffet intensity rise occurred. The increased tracking error may have been due to subjecting the pilot to the steady-state load factor in combination with the cockpit vibration and wing rock. The pilots appeared to become somewhat more accustomed to the buffeting, and made fewer comments about it, as the program progressed.

Figure 14 presents a representative time history of a tracking windup turn at Mach 0.89 and an altitude of 10,700 meters in which wing rock was encountered at an angle of attack of 10° . The maximum roll rate reached ± 20 degrees per second, and it is apparent that the ARI did not command enough rudder to counter the sideslip generated by the aerodynamic cross coupling. The effect of this wing rock on tracking precision is illustrated in figure 15. Wing rock onset occurred at a time of approximately 28 seconds in this run, allowing the pilot to track for 28 seconds without wing rock and for 17 seconds in the presence of wing rock. The rms tracking error for the entire run is not indicative of precision controllability in the presence of wing rock because so much time was wing rock free; instead, a comparison of the tracking error time history before and after wing rock onset yields the desired information. The radial rms tracking error is 6 mils before

wing rock onset and 14 mils in the presence of wing rock. In other words, tracking error approximately doubled in the presence of wing rock. Comparing the tracking errors in figure 15 with those in figure 9 (in which there was no wing rock) indicates the tracking before wing rock onset in figure 15 to be slightly better than in figure 9 (6.0 mils versus 8.7 mils) and significantly poorer after wing rock onset (14.0 mils versus 8.7 mils). Figure 15 also shows the greater error while tracking in the presence of wing rock to lie in the azimuth axis. An analysis of all the runs in which wing rock was encountered on the F-15 airplane indicated a doubling of the radial tracking error in the presence of wing rock.

Reference 4 tracking results.—Approximately 100 constant g tracking runs were made with a production airplane at the flight conditions indicated in figure 2 during the AFFTC F-15 development, test, and evaluation flight program reported in reference 4. The runs were conducted with two pilots, two external store loadings and CAS configurations, and two ARI schedules. Figure 16 summarizes the reference 4 runs as a function of angle of attack for the air superiority loading (the flight condition nearest the clean configuration used in the DFRC study) for CAS on and off and the cruise ARI schedule. The caged gunsight pipper was depressed 125 mils for the reference 4 tracking study, and flights were made both with and without pilot rudder inputs. The wing rock angle of attack region was not penetrated in this study; however, the 125 mil pipper depression angle probably aggravated the pendulum effect at the lower angles of attack more than the 70 mil depression angle used during the DFRC study. In addition, the more aggressive tracking maneuver used by the AFFTC (in which the run is started with the pipper displaced from the target and the aim point is acquired as rapidly as possible after data acquisition begins) would tend to make the rms tracking error slightly larger in the AFFTC study than in the DFRC study. A number of CAS-off runs were performed (solid symbols in fig. 16), and they generally showed a tracking error that was 2 to 4 mils larger than with the CAS on.

The second ARI schedule evaluated in the reference 4 study was the flaps-down ARI schedule, which yielded two degrees more proverse rudder than the cruise schedule. These runs (which are not presented in fig. 16) showed slightly better tracking than with the cruise schedule.

An analysis of the reference 4 tracking study presented in figure 16 shows the CAS-on rms radial tracking error to vary from approximately 4 to 12 mils for the two Mach numbers investigated. The CAS-off error varied from 6 to 22 mils rms. The CAS-on DFRC data generally agreed well with the CAS-on reference 4 data.

CONCLUDING REMARKS

Ten caged pipper windup turn tracking flights were conducted with a preproduction F-15 airplane by two Dryden Flight Research Center (DFRC) pilots. The first six flights were conducted with the prototype control system, whereas the last four flights followed an effort to upgrade the control system to production status. Flights were also made to evaluate the airplane's buffet and wing rock characteristics. The following remarks are based on the data produced by this flight program.

The F-15 airplane radial tracking precision varied from approximately 6 to 20 mils over the load factor range to 8.0 g's.

The effects of the airplane's flight control system on tracking precision were pronounced. With the augmentation system on, the pitch axis evidenced a low-amplitude, high-frequency oscillation. Lateral-directional response was generally typified as being sluggish. The sluggishness was attributed, at least in part, to hysteresis in the directional control system that prevented the aileron-to-rudder interconnect (ARI) from applying enough rudder to overcome the adverse aileron yaw. This would tend to aggravate the pendulum effect produced by the depressed, caged pipper gunsight. Limited data indicated that turning the augmentation system off reduced the pitch oscillation frequency but increased the lateral-directional sluggishness.

Buffet intensity at the higher angles of attack was severe, but, with regard to tracking, it was difficult to separate buffet from control system effects. Wing rock at the higher angles of attack was moderate, and the rms tracking errors in the presence of wing rock were approximately double those experienced at lower angles of attack. The degradation might have been greater, except that tracking errors at low angles of attack were already large as a result of adverse control system influences.

Upgrading the control system to production status did not improve tracking precision.

The precision controllability found in this study agreed well with the results of a constant g tracking study conducted by the Air Force Flight Test Center on a production airplane.

*Dryden Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., December 1, 1978*

APPENDIX—F-15 CONTROL SYSTEM DESCRIPTION

The mechanical control system distributes pilot commands to hydraulic actuators, which move the stabilators, ailerons, and rudders. The stabilators deflect collectively for pitch control and differentially to add roll control power to the ailerons. An automatic flight control system (AFCS) was also incorporated to provide improved flying qualities, automatic flightpath control, and trim control. The mechanical flight control system and the CAS mode of the AFCS were designed to provide military specification (ref. 8) handling qualities. The mechanical control system was designed to permit the completion of the mission after the loss of the AFCS or to permit the airplane to be flown safely through the CAS after the failure of the mechanical control system.

Longitudinal Axis

The longitudinal mechanical stick force characteristics, showing trim authority and breakout force, are illustrated in figure 17. The control-stick-to-stabilator gearing ratio is determined by the pitch ratio adjust device (PRAD), which is scheduled as a function of dynamic pressure and Mach number. The pitch trim compensator (PTC) supplies the series trim to the longitudinal control system by summing its position with the pilot input. This function compensates for changes in trim caused by changes in speed, flap deflection, speed brake deflection, and store separation.

Pitch command augmentation blends airplane normal acceleration and washed-out pitch rate to form a C* feedback system. The longitudinal command system feel characteristics are depicted in figure 18. The maximum pitch CAS authority is $\pm 10^\circ$ of stabilator; however, the variable pitch CAS limiter reduces this authority when mechanical stabilator commands exceed 5° and -19° . Gunsight tracking runs by both AFFTC and DFRC pilots showed this system to be extremely sensitive with CAS on.

Lateral Axis

The lateral mechanical stick force characteristics, showing trim authority and breakout force, are illustrated in figure 19. Lateral mechanical advantage is provided by the roll ratio adjust device (RRAD) and is scheduled with longitudinal collective stabilator position as shown in figure 20. The mechanical advantage is adjusted at high speeds by hydromechanical control system feedback scheduled as a function of calibrated airspeed.

Roll command augmentation is provided through the stabilator CAS series servos according to the schedule shown in figure 21. The differential stabilator-to-stick gearing ratio is 0.3° of differential stabilator per degree of aileron deflection except where restricted by the stabilator actuator limits. Dynamic pressure and angle of attack limit schedules are incorporated into the CAS variable limiter.

Directional Axis

Directional control is provided hydromechanically through rudder pedals with the force and trim characteristics depicted in figure 22. Rudder-to-pedal gearing is fixed at 1.8° of rudder per centimeter of differential pedal position.

The primary purpose of the yaw CAS is to provide Dutch roll damping, and it is limited to $\pm 5^\circ$ of rudder deflection.

A significant amount of rudder pedal breakout force and rudder hysteresis was noted in the ground calibration described in reference 4 and was reported by both AFFTC and DFRC pilots as a major handling qualities deficiency. The hysteresis made the ARI less effective and affected tracking both with and without pilot rudder inputs.

Lateral-Directional Coordination

Maneuvering lateral control coordination is provided by an ARI, which is scheduled as a function of stabilator position for two flap settings (fig. 23). For the flaps-retracted configuration, the ARI provides rudder to counter adverse yaw at angles of attack above approximately 3° for all speeds below Mach 1. If figures 20 and 23 are considered together, it becomes apparent that the ARI provides three gradients: a nearly zero gradient through neutral longitudinal control position, 0.55° of proverse rudder per degree of aileron for back stick force, and 0.85° of adverse rudder per degree of aileron for forward stick force. This schedule is the result of modifications made during the AFFTC development test and evaluation flight program, and there is still some question as to whether it is optimum. The large directional control system breakout force and hysteresis may be influencing this belief.

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TABLE 1.—F-15 DIMENSIONS

Airplane—

Length, m	19.06
Height, m	5.68
Takeoff gross weight (with AIM-7F missiles), kN	180

Wing—

Area (reference), m ²	56.61
Span, m	13.05
Aspect ratio	3.0
Taper ratio	0.25
Dihedral, deg	-1.0
Geometric twist, deg	0
Incidence, deg	0
Leading-edge sweep, deg	45.0
Mean aerodynamic chord, m	4.86

Ailerons—

Type	Plain sealed
Maximum deflection, deg	±20
Span (total), m	3.30
Area (total), m ²	2.46

Horizontal stabilators—

Area (total), m ²	11.15
Span, m	8.61
Aspect ratio	2.046
Taper ratio (exposed)	0.34
Dihedral, deg	0
Geometric twist, deg	0
Deflection limits, deg	15, -26
Leading-edge sweep, deg	50.0
Root chord (exposed), m	3.48
Tip chord, m	1.18

Vertical stabilizers—

Area, m ²	11.63
Span (exposed), m	3.15
Aspect ratio	1.70
Taper ratio	0.27
Leading-edge sweep, deg	34.57

Root chord (exposed), m	.	.	.	.	.	.	.	.	.	2.92
Tip chord, m	.	.	.	.	.	.	.	.	.	0.78

Rudders—

Maximum deflection, deg	.	.	.	.	.	.	.	.	.	±30.0
Span, m	.	.	.	.	.	.	.	.	.	1.44
Area (total), m ²	.	.	.	.	.	.	.	.	.	6.07

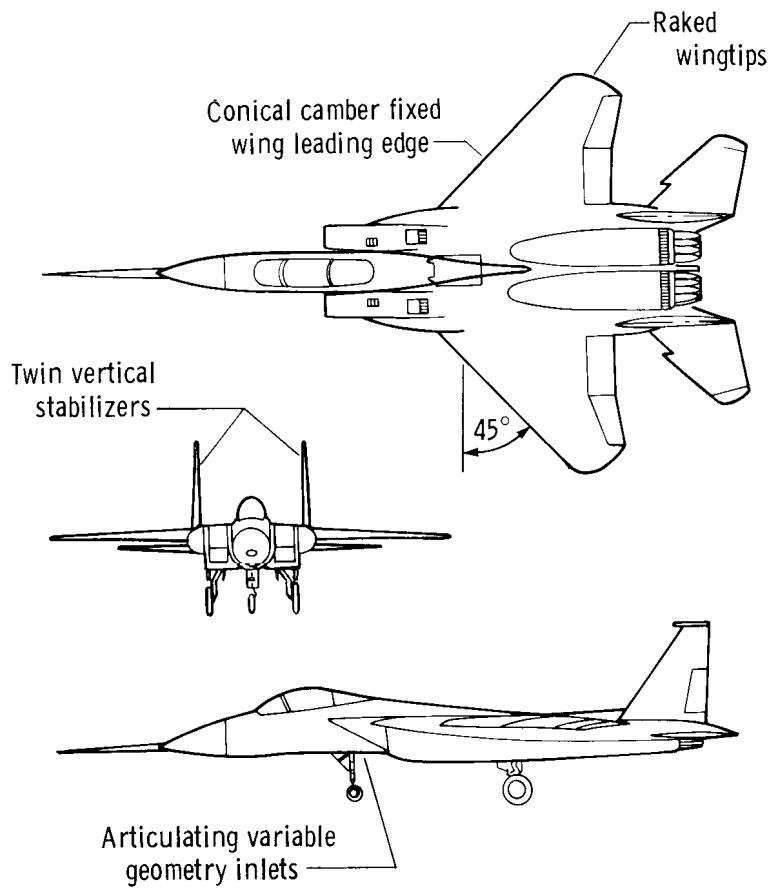


Figure 1. F-15 airplane.

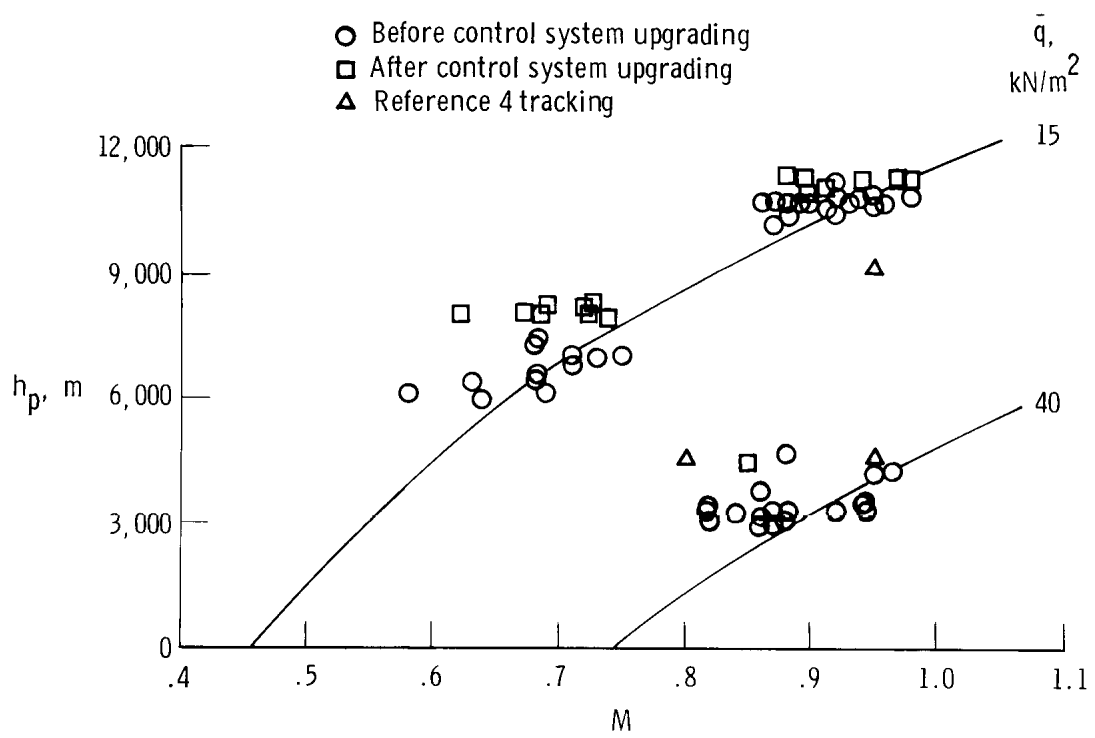


Figure 2. Program test conditions.

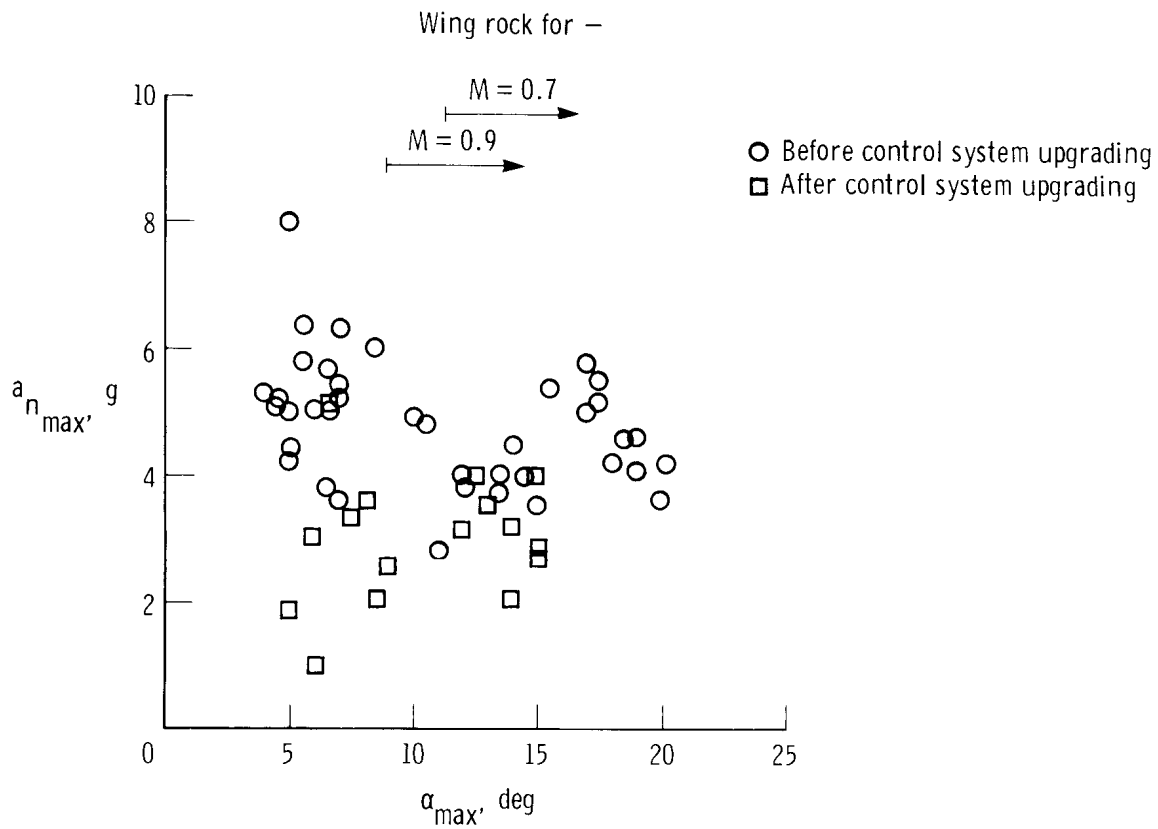


Figure 3. Program normal load factor/angle of attack envelope.

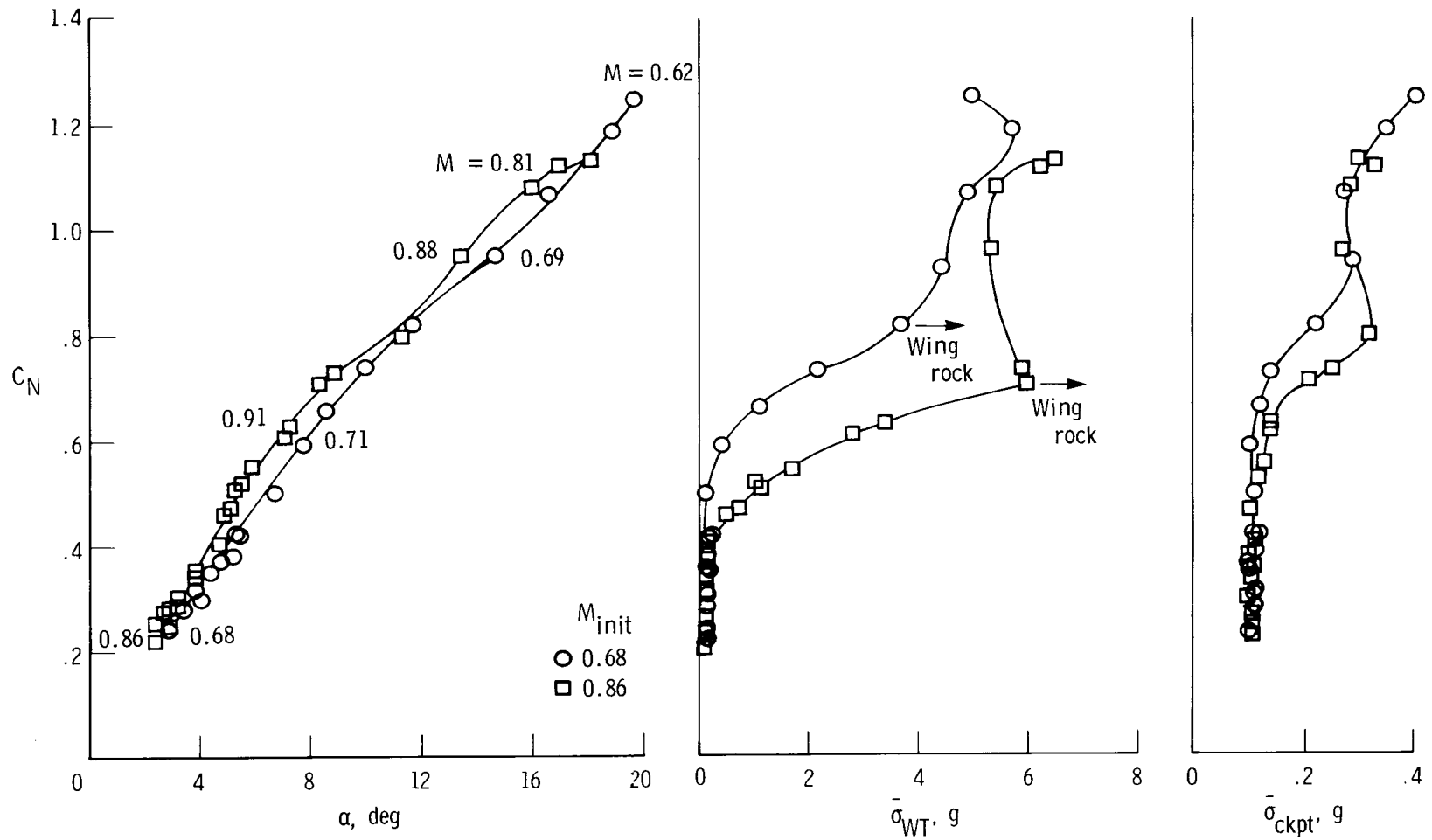
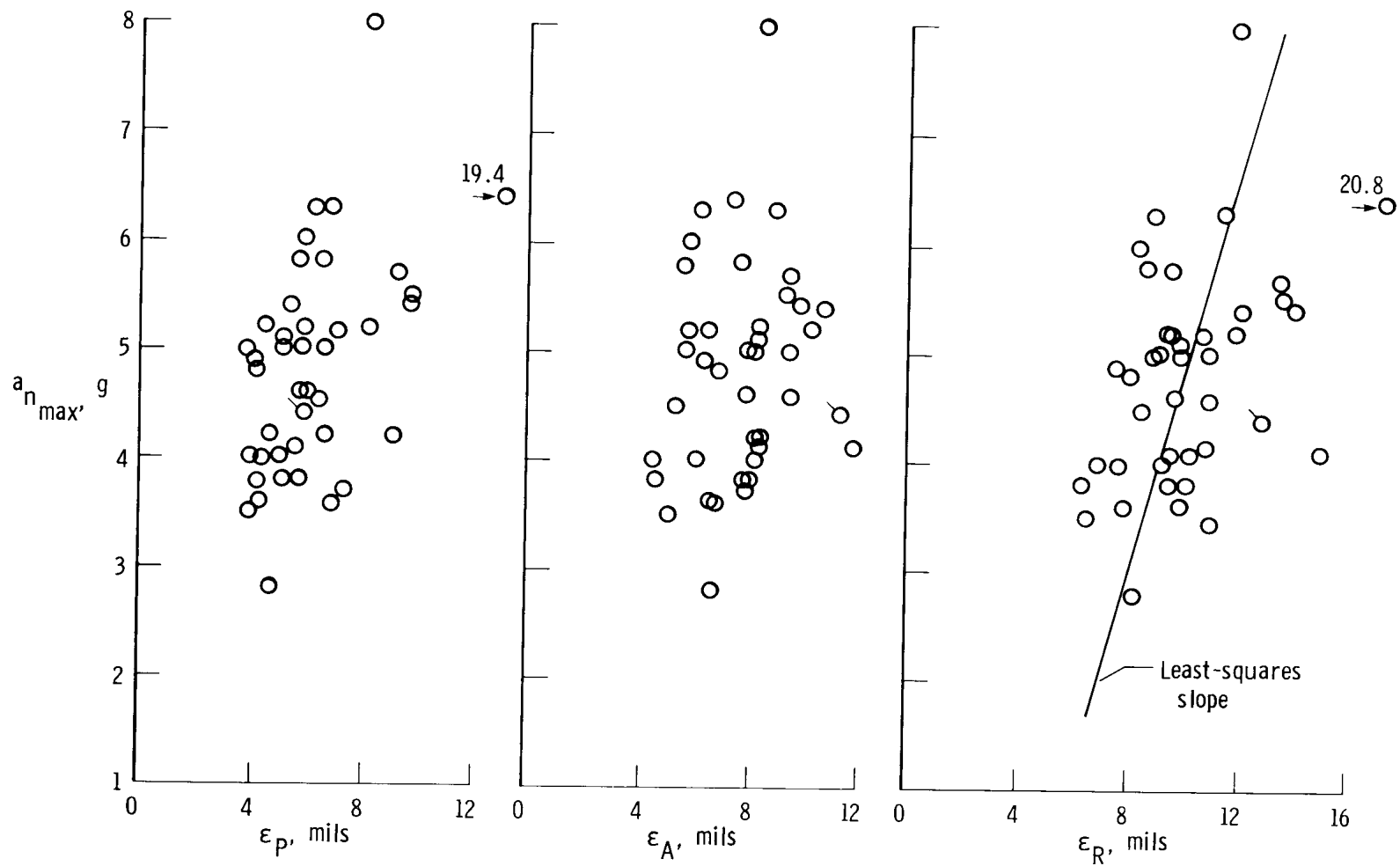
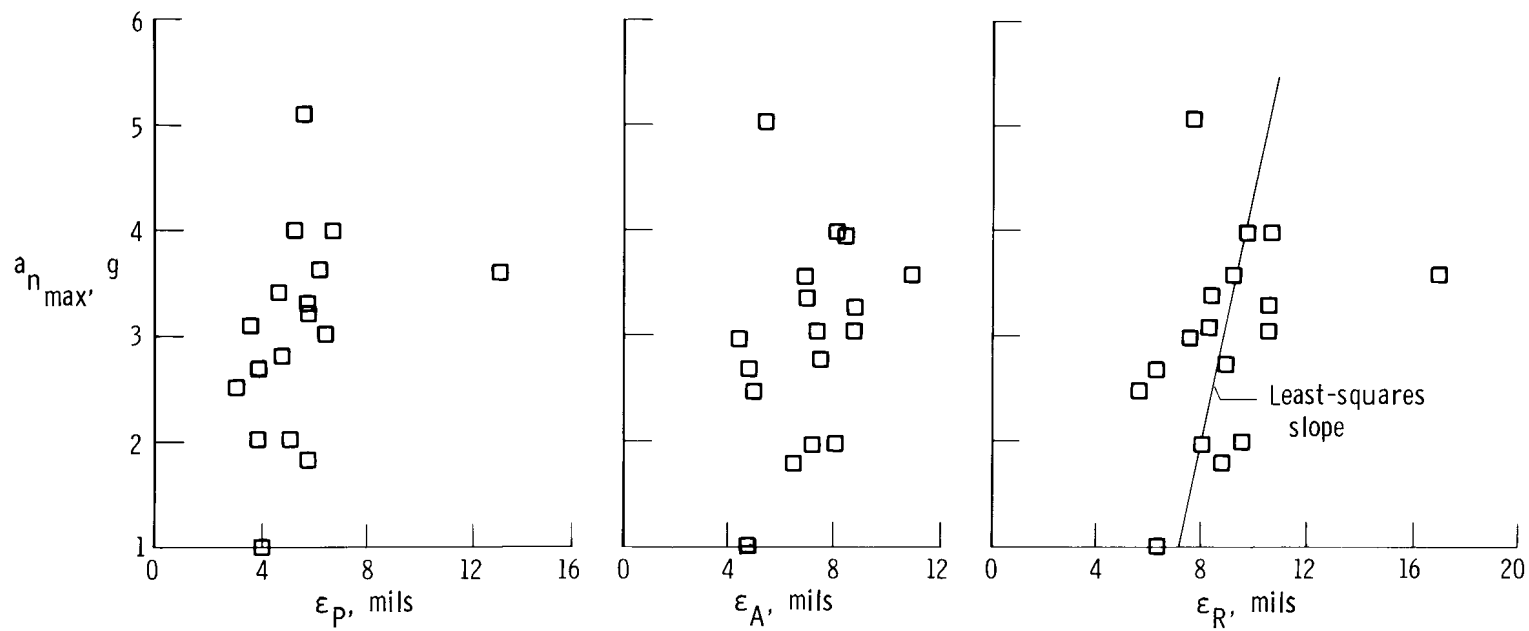


Figure 4. Aerodynamic performance and buffet characteristics of F-15 airplane with raked wingtips. Windup turn maneuver with thrust as required to maintain constant Mach number; buffet normalized to 14.36 kN/m^2 .



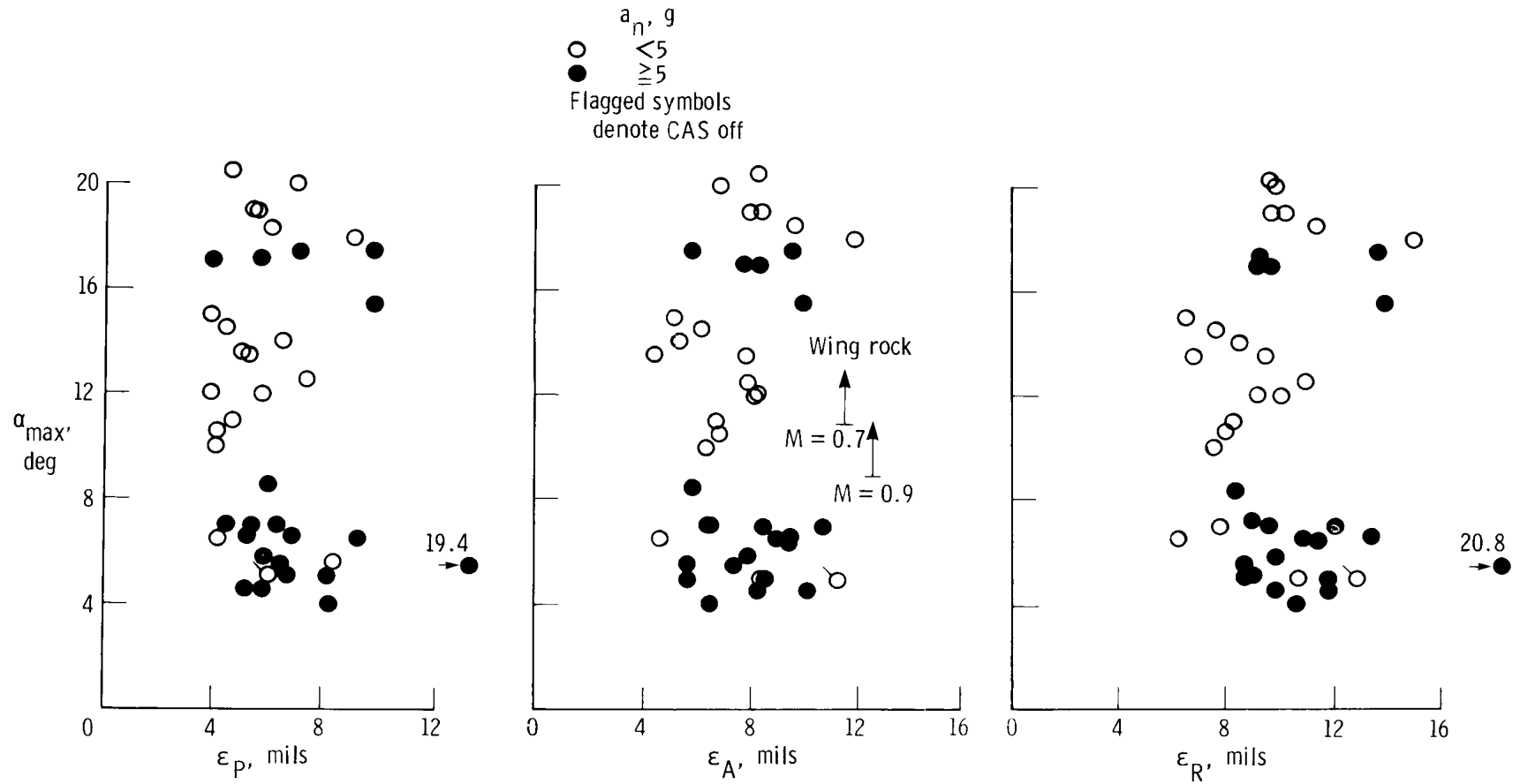
(a) Before control system upgrading. Flagged symbols denote CAS off.

Figure 5. Tracking error summary versus maximum normal load factor. $M = 0.58$ to 0.98 ; $h_p = 3000$ to $11,300$ m; CAS on; gunsight depression angle = 70 mils.



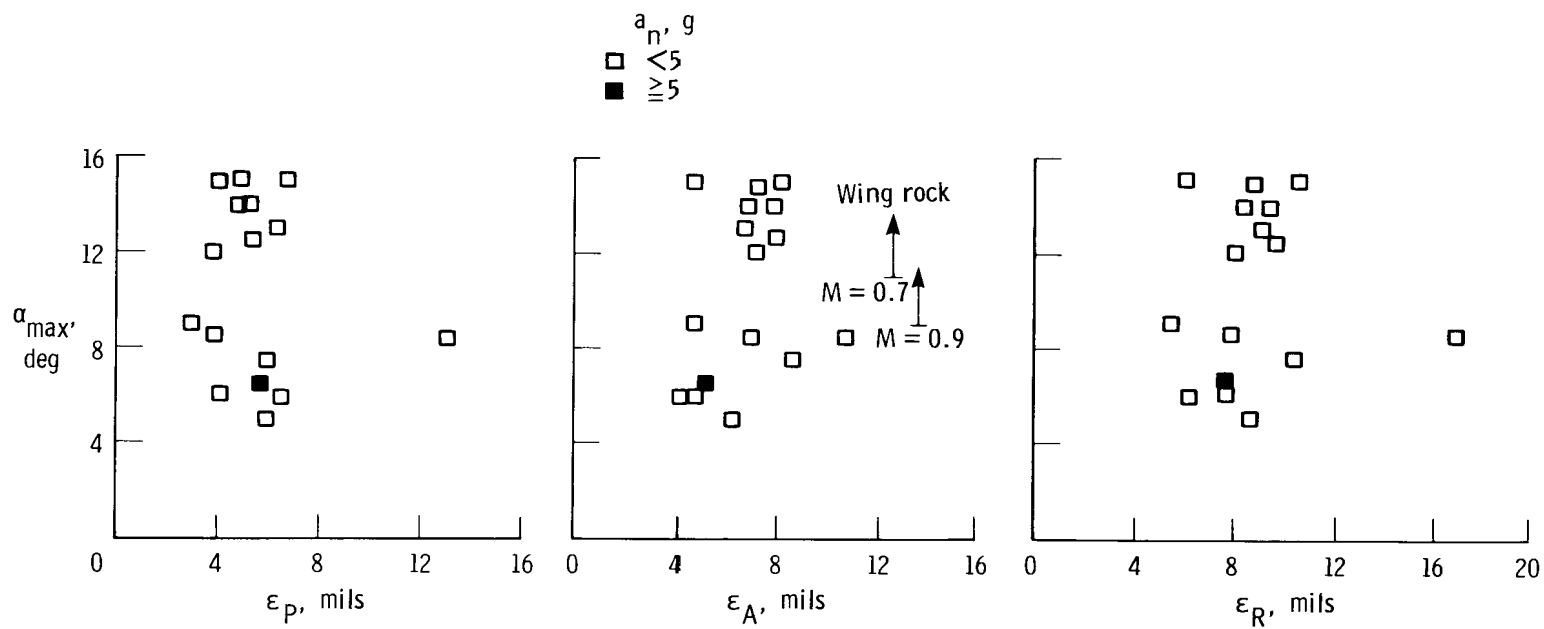
(b) After control system upgrading.

Figure 5. Concluded.



(a) Before control system upgrading.

Figure 6. Tracking error versus maximum angle of attack. $M = 0.58$ to 0.98 ; $h_p = 3000$ to $11,300$ m; CAS on; gunsight depression angle = 70 mils.



(b) After control system upgrading.

Figure 6. Concluded.

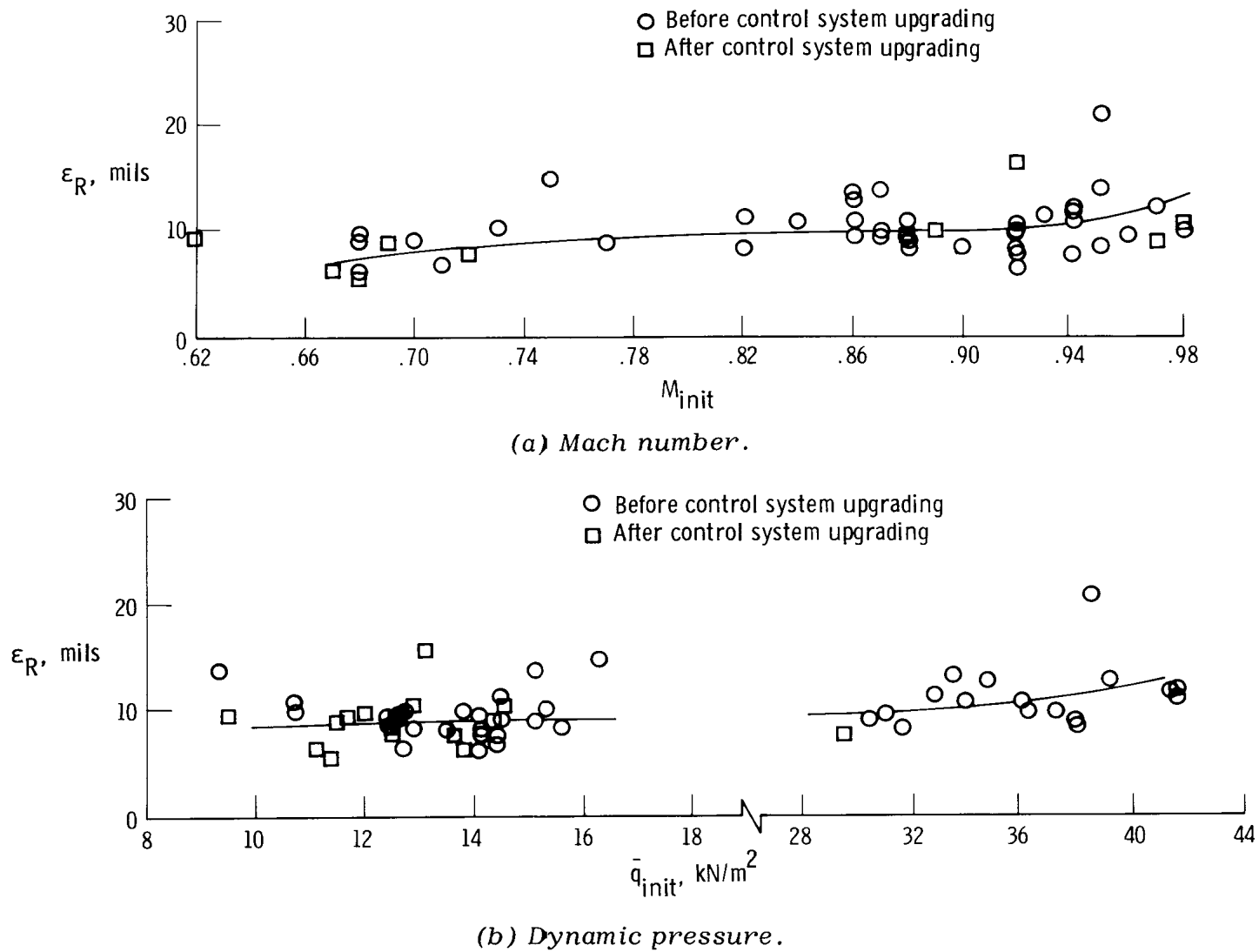
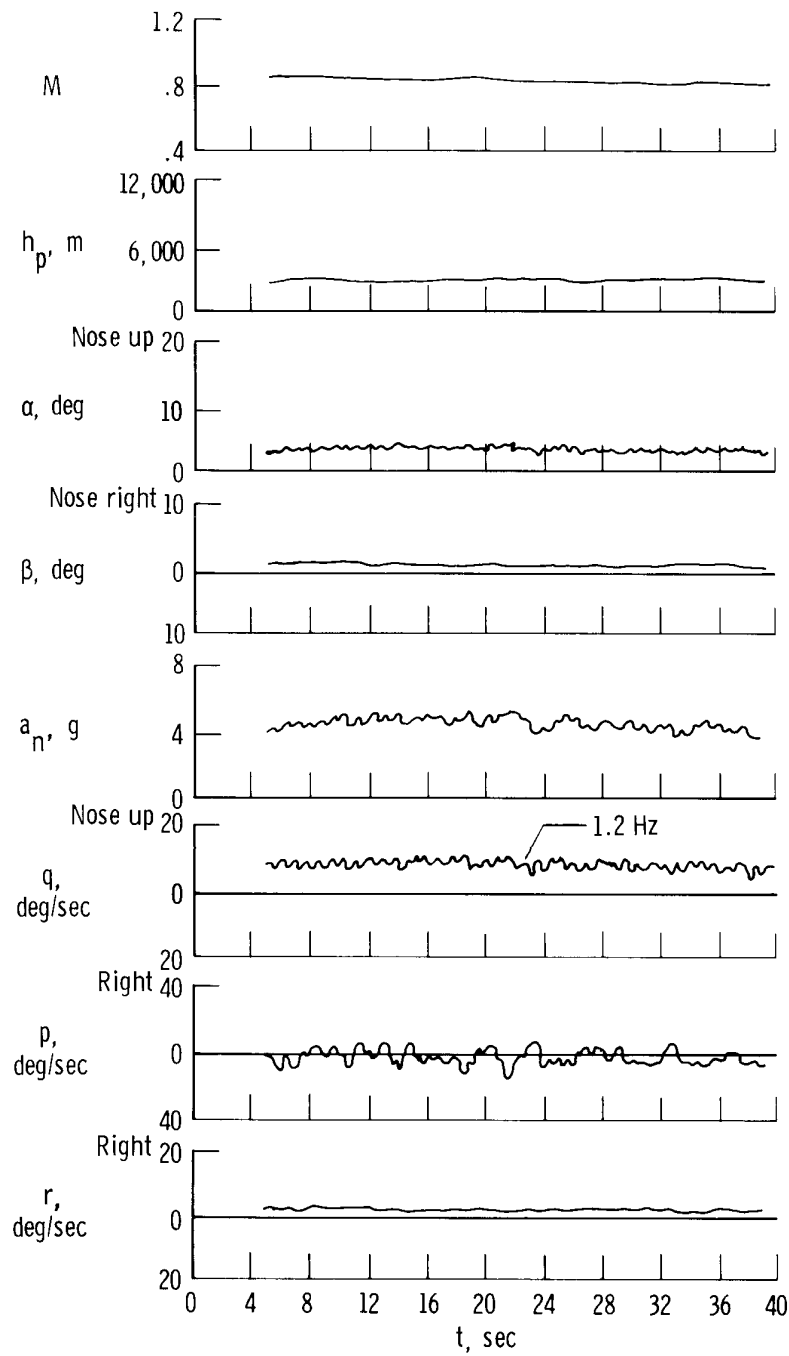
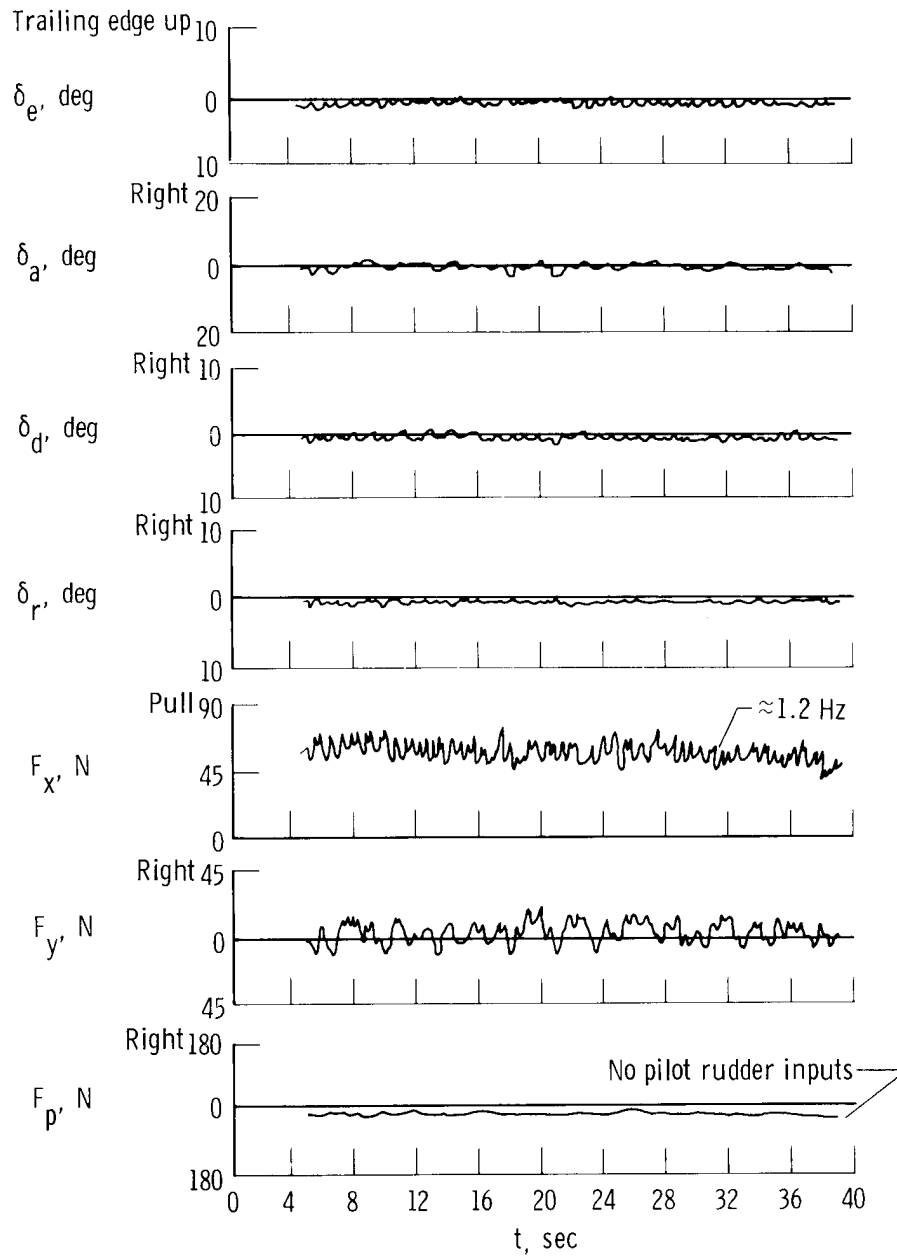


Figure 7. Radial tracking error variation with Mach number and dynamic pressure.



(a) Airplane response parameters.

Figure 8. Constant g tracking time history illustrating pitch sensitivity. $M = 0.86$; $h_p = 3200$ m; CAS on.



(b) Airplane control parameters.

Figure 8. Concluded.

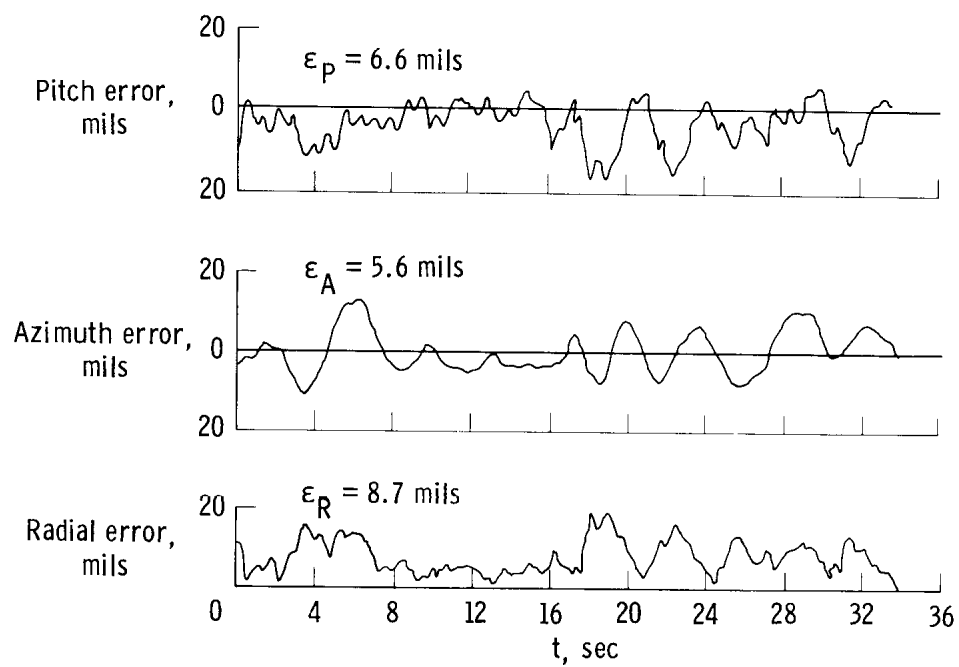


Figure 9. Tracking error for time history shown in figure 8. $M = 0.86$; $h_p = 3200$ m; $a_n \approx 4.5$ g's; CAS on; gunsight depression angle = 70 mils.

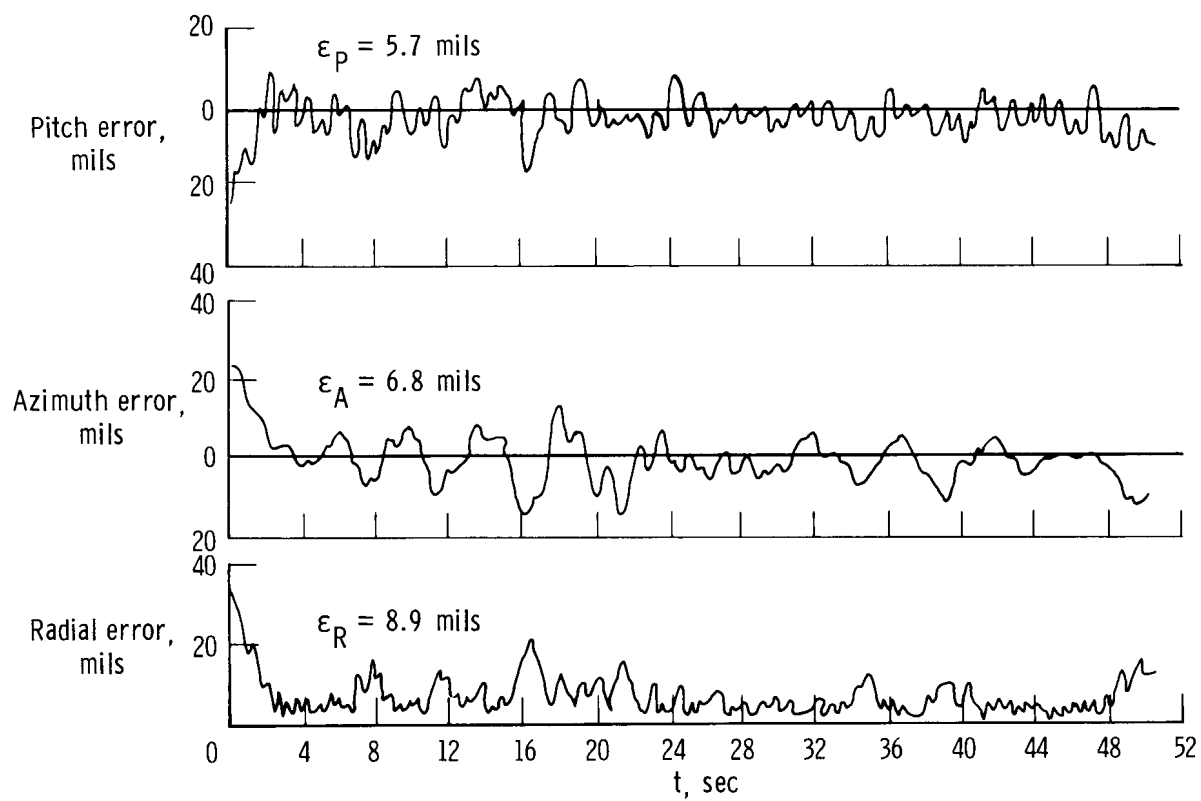
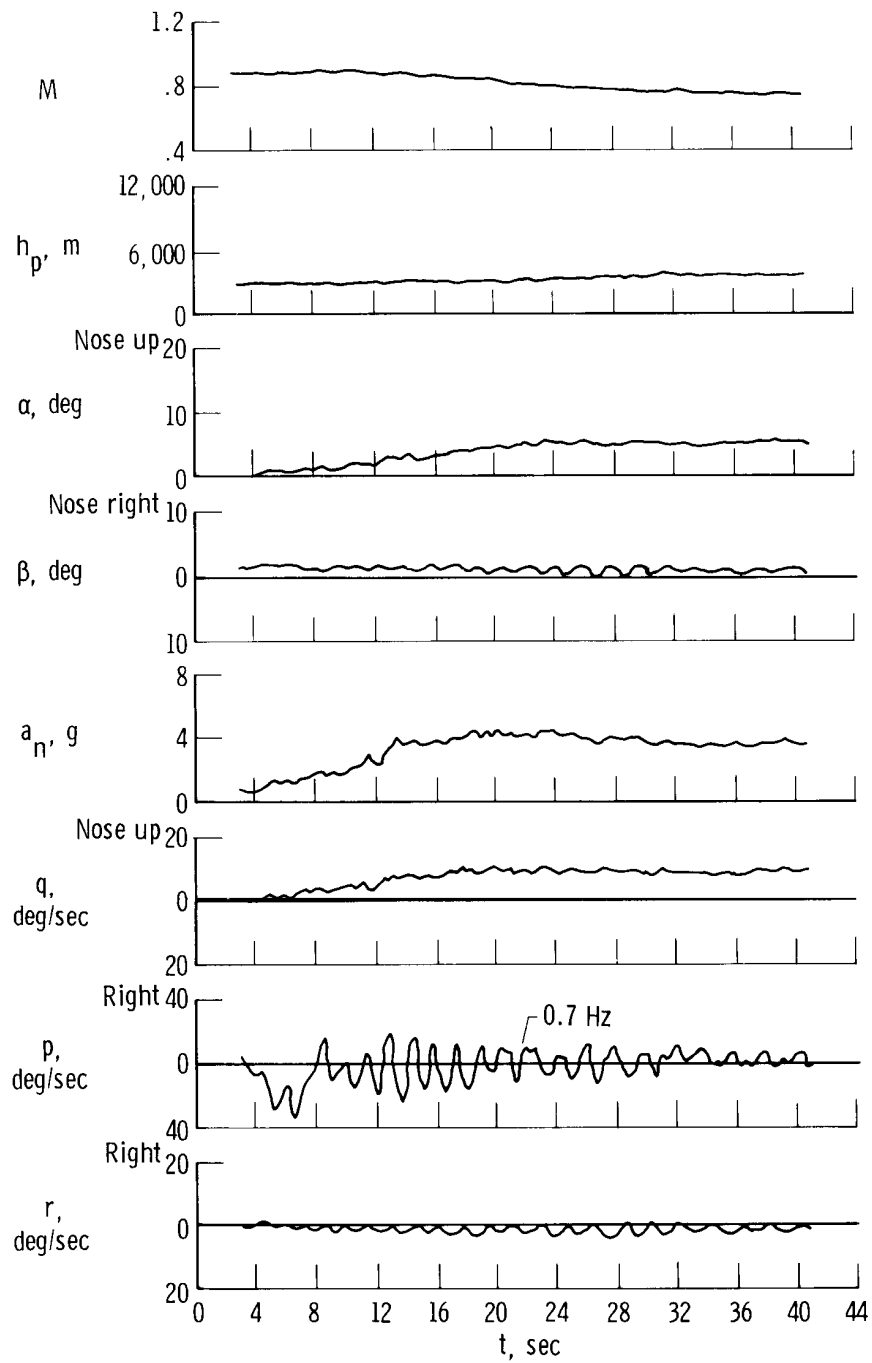
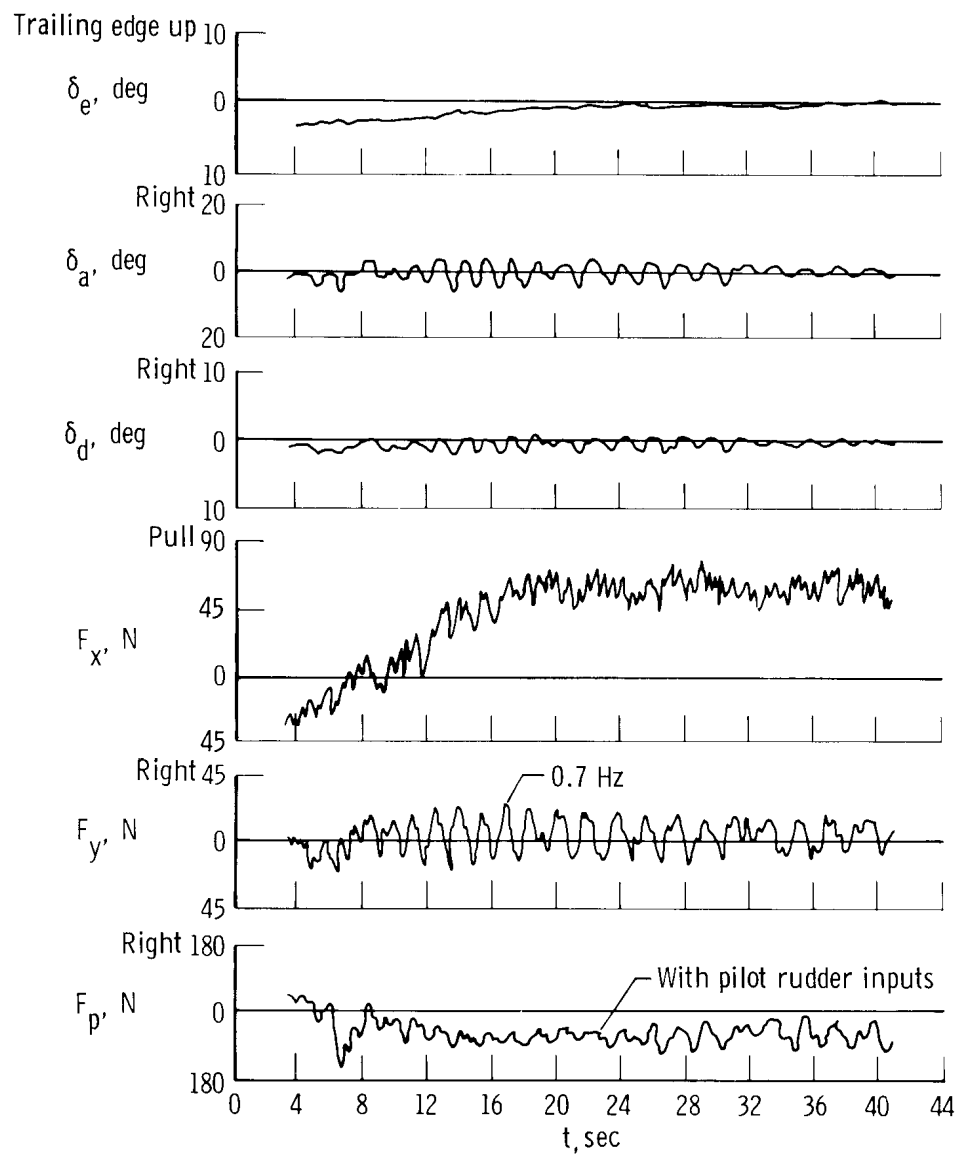


Figure 10. Tracking error for time history from reference 4. $M = 0.80$; $h_p = 6700$ m; CAS on; gunsight depression angle = 125 mils.



(a) Airplane response parameters.

Figure 11. Windup turn tracking time history illustrating lateral sensitivity. $M = 0.87$; $h_p = 3048$ m; CAS off.



(b) Airplane response parameters.

Figure 11. Concluded.

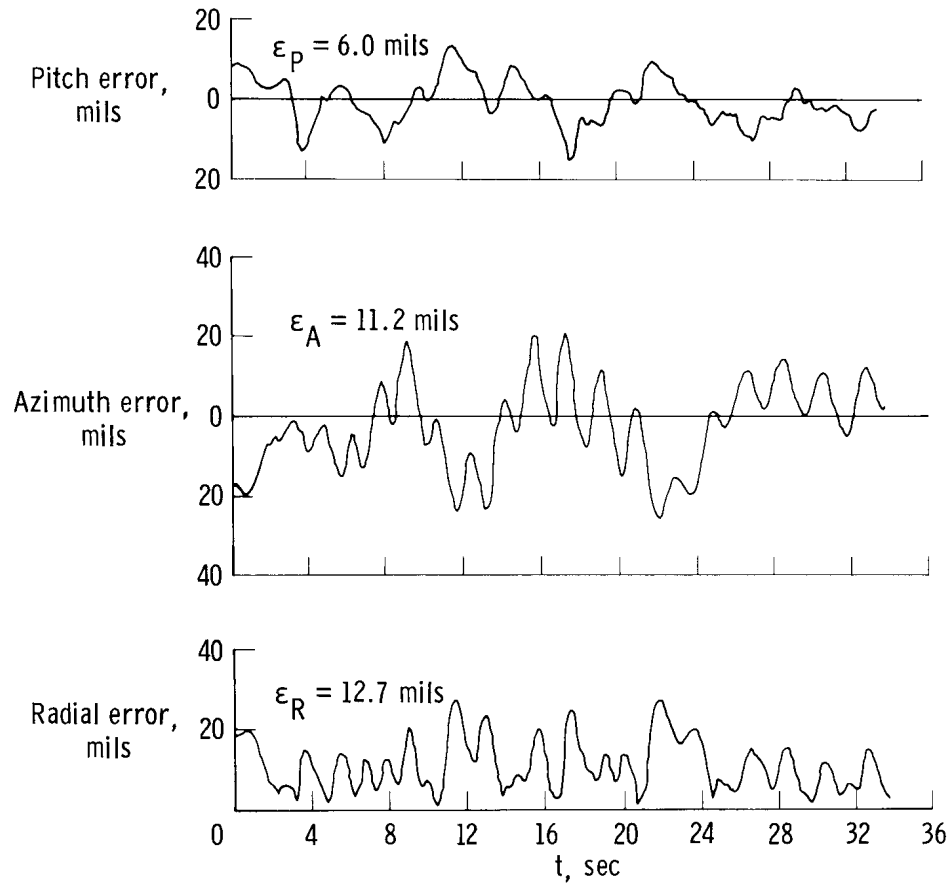


Figure 12. Tracking error for time history shown in figure 11. $M = 0.87$; $h_p = 3048$ m; $a_n \approx 4.0$ g's; CAS off; gunsight depression angle = 70 mils.

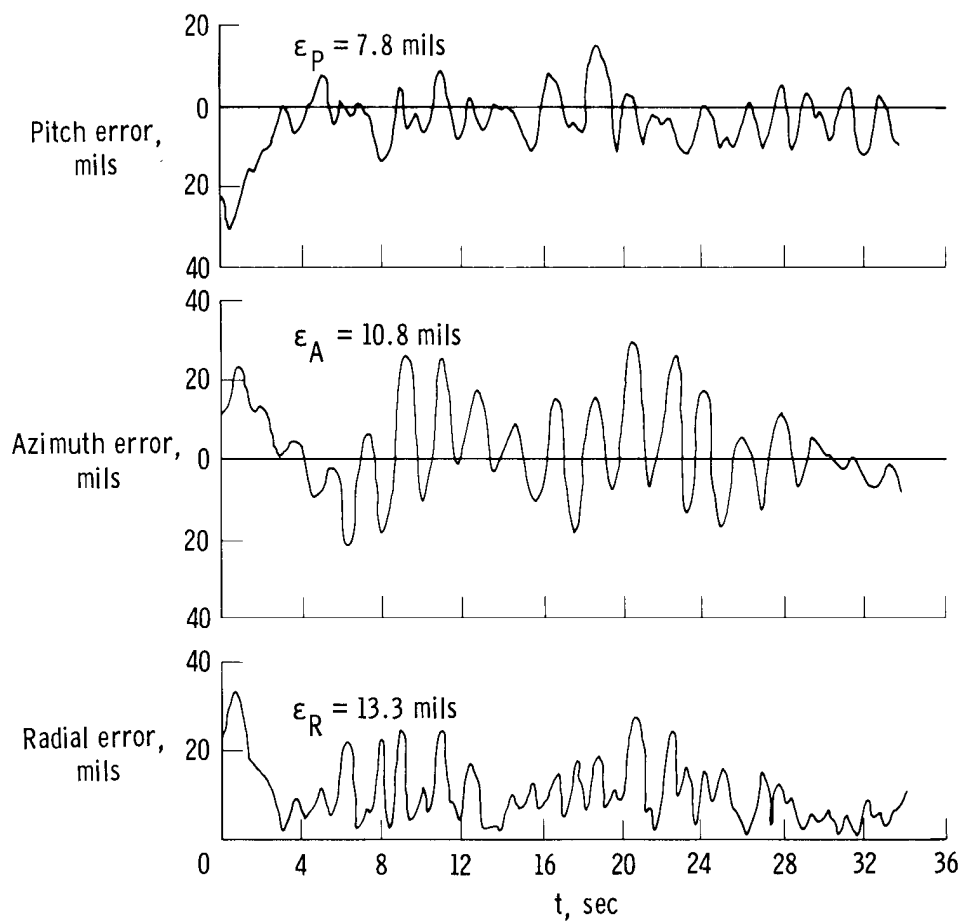
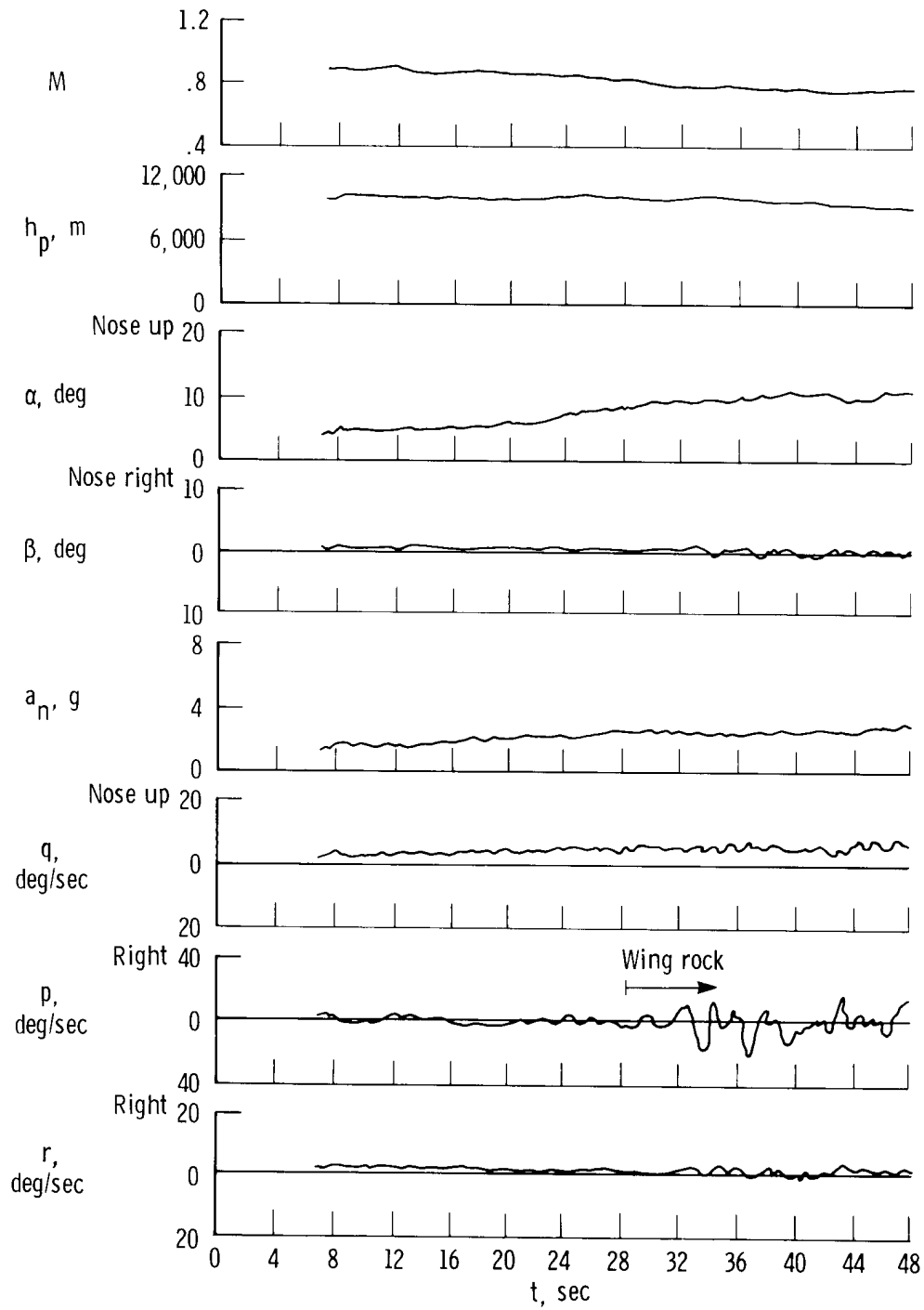
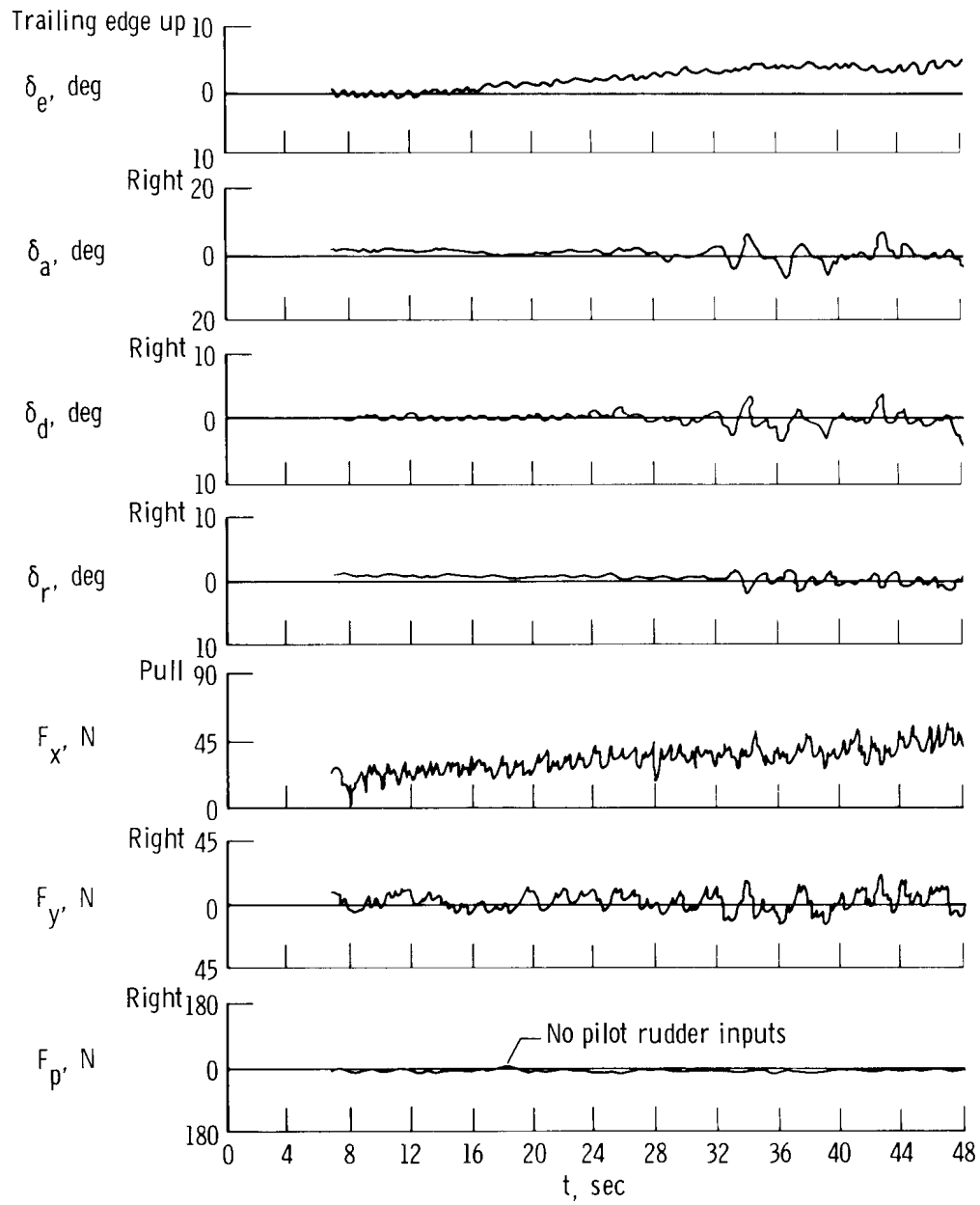


Figure 13. Tracking error for time history from reference 4. $M = 0.80$; $h_p = 6700$ m; CAS off; gunsight depression angle = 125 mils.



(a) Airplane response parameters.

Figure 14. Windup turn tracking time history illustrating wing rock. $M = 0.89$; $h_p = 10,700$ m; CAS on.



(b) Airplane control parameters.

Figure 14. Concluded.

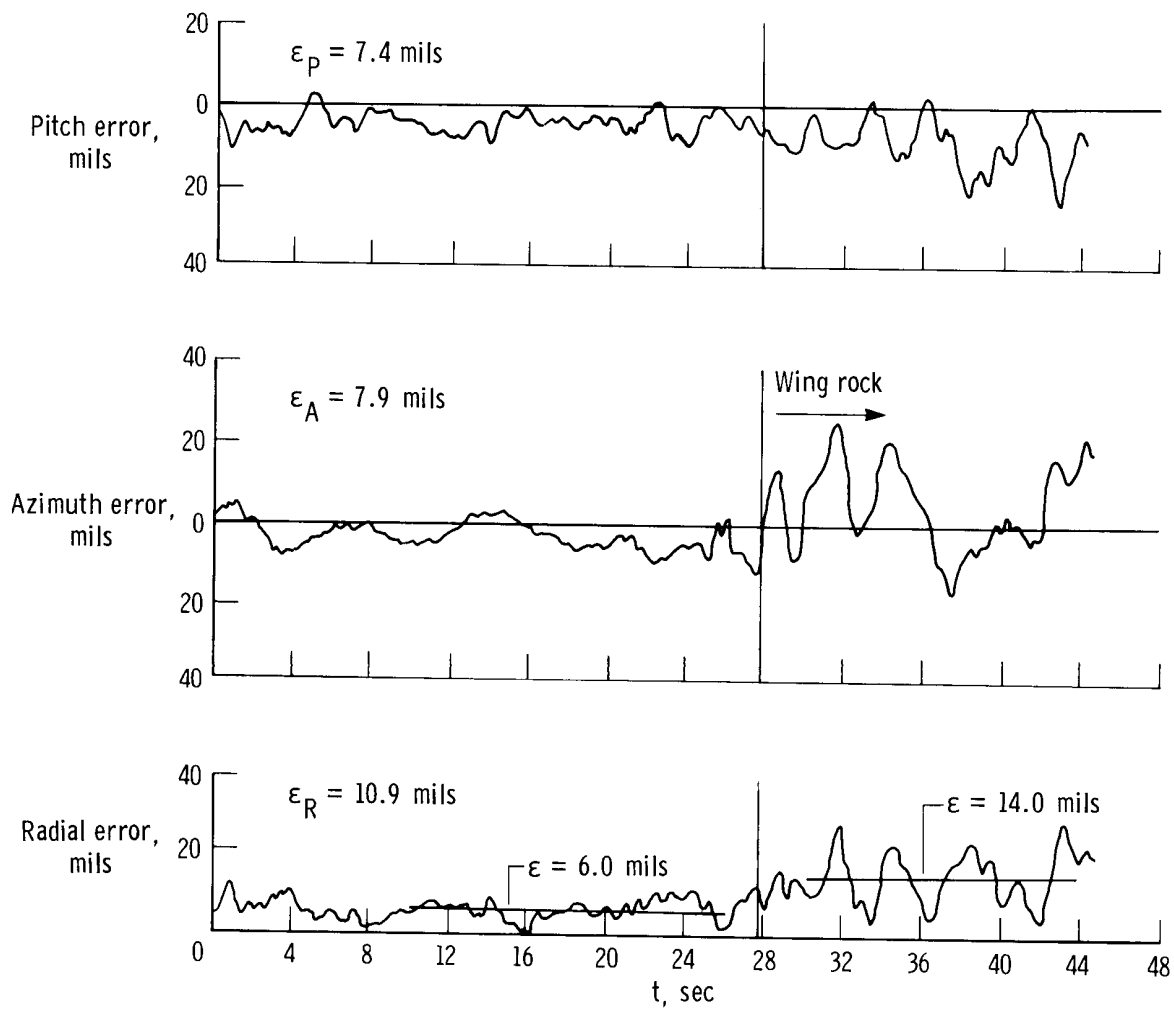


Figure 15. Tracking error time history of figure 14. $M = 0.89$; $h_p = 10,700$ m; $a_n = 1.5$ to 3.5 g's; CAS on; gunsight depression angle = 70 mils.

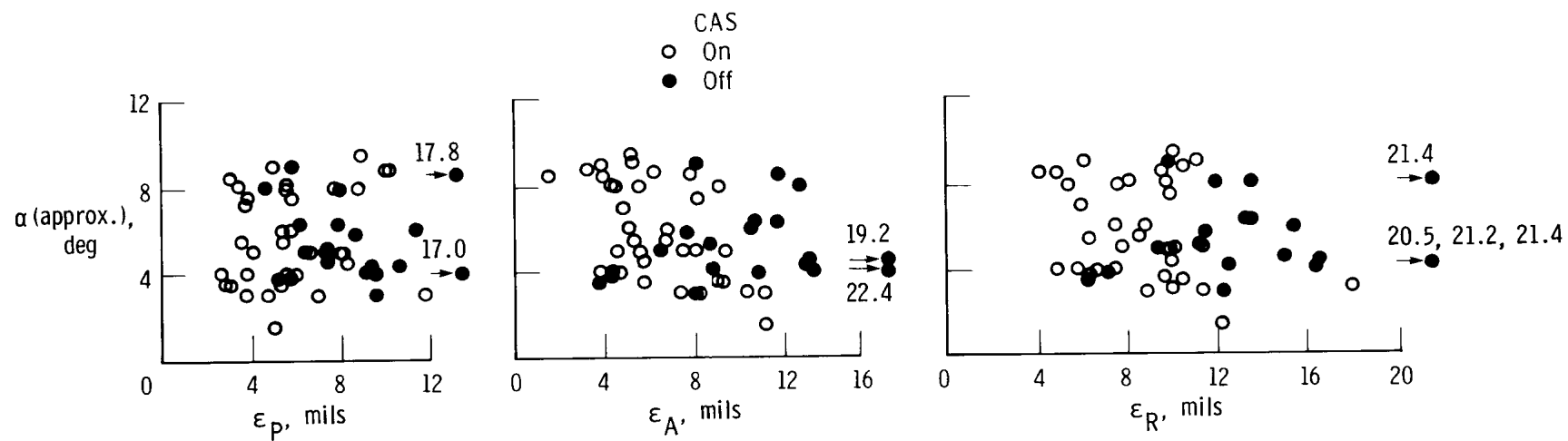
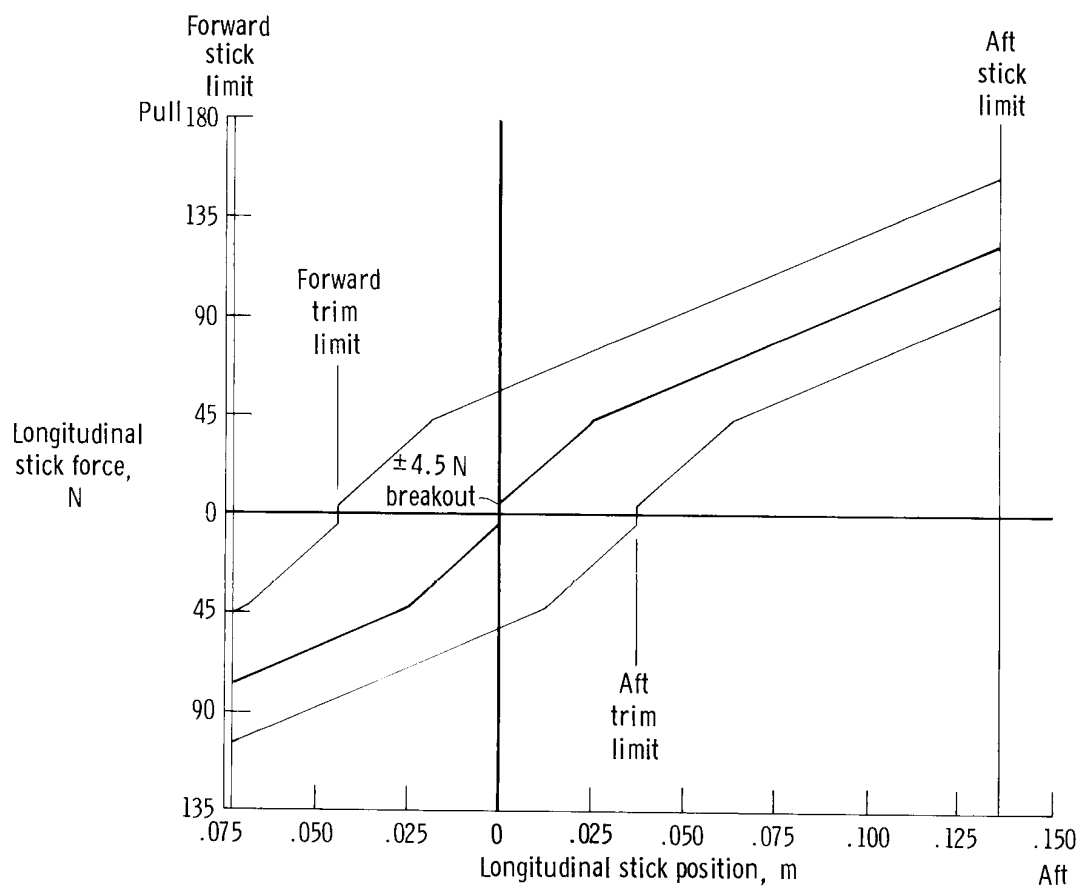


Figure 16. Reference 4 tracking error versus maximum angle of attack. Air superiority loading; $M = 0.8$ to 0.95 ; $h_p = 4500$ to 9000 m; gunsight depression angle = 125 mils.



17. Longitudinal mechanical stick force characteristics (ref. 4).

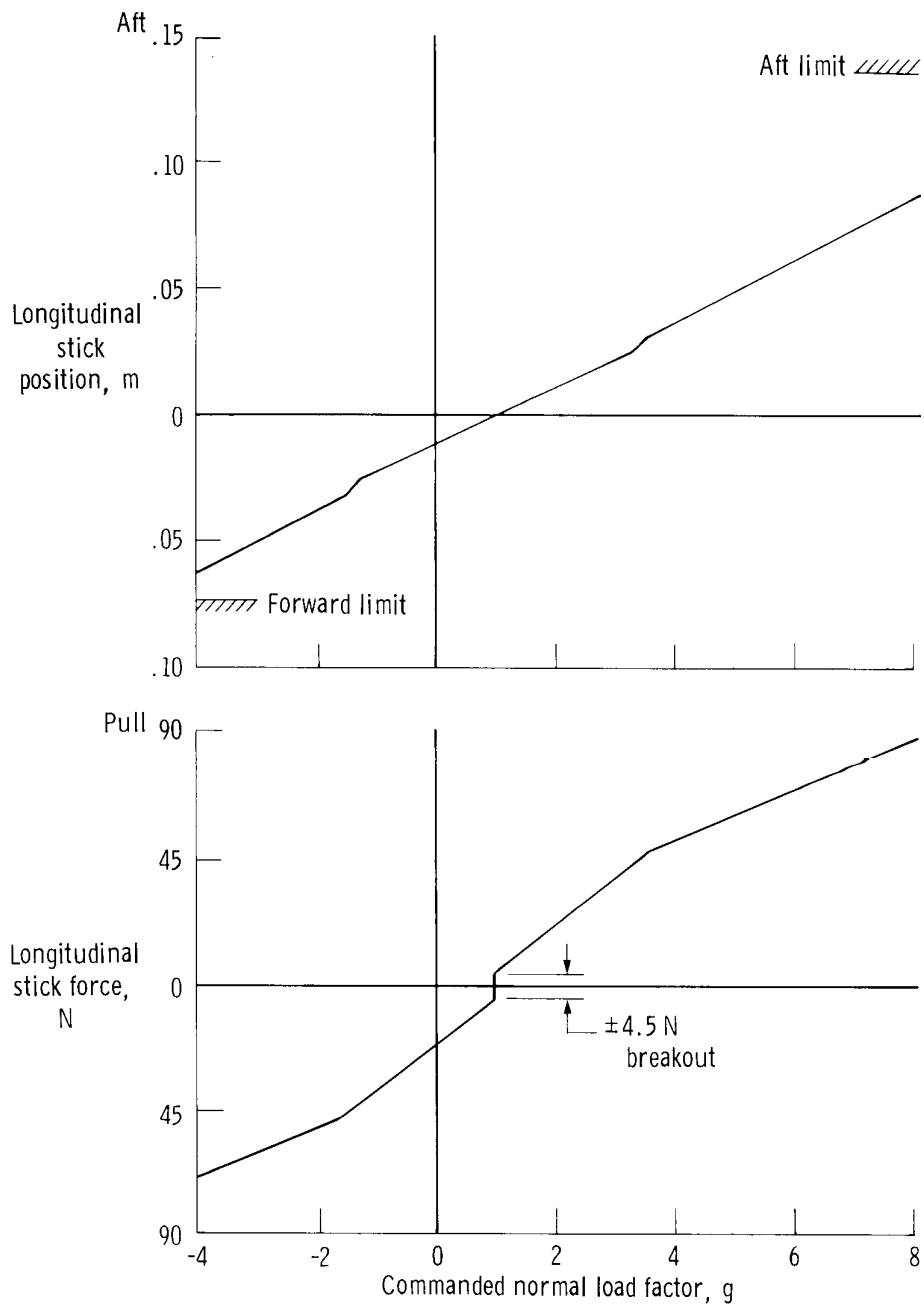


Figure 18. Longitudinal CAS feel characteristics (ref. 4).

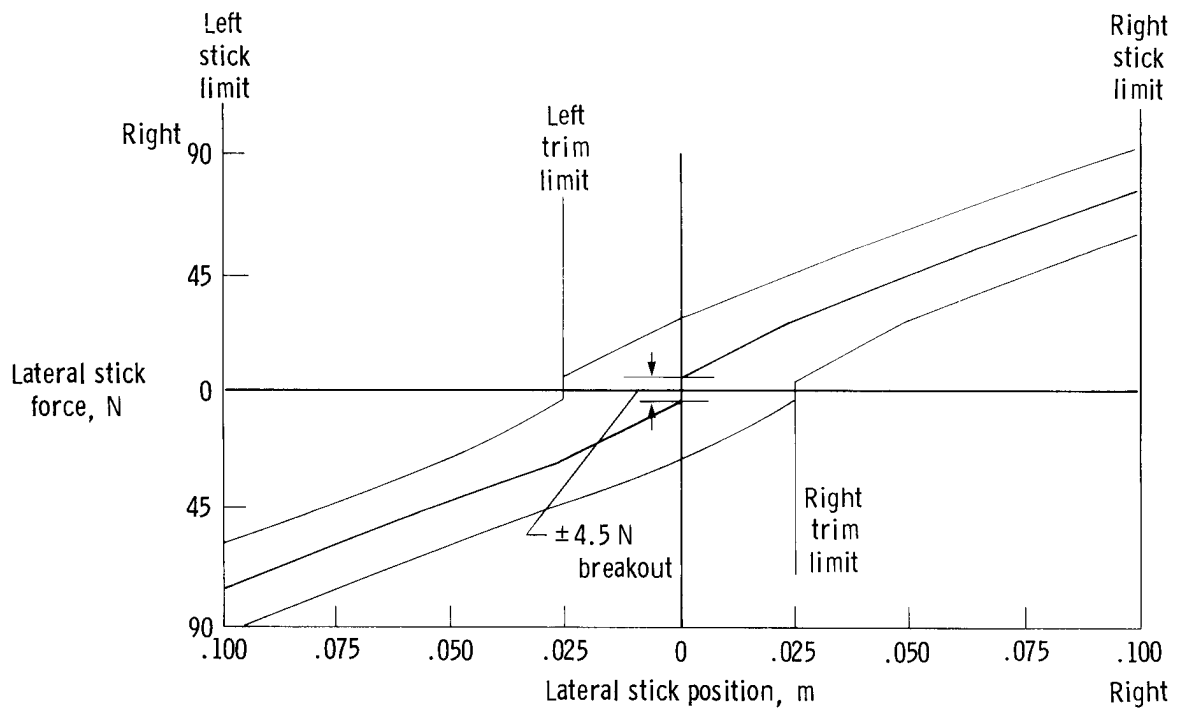


Figure 19. Lateral stick force characteristics (ref. 4).

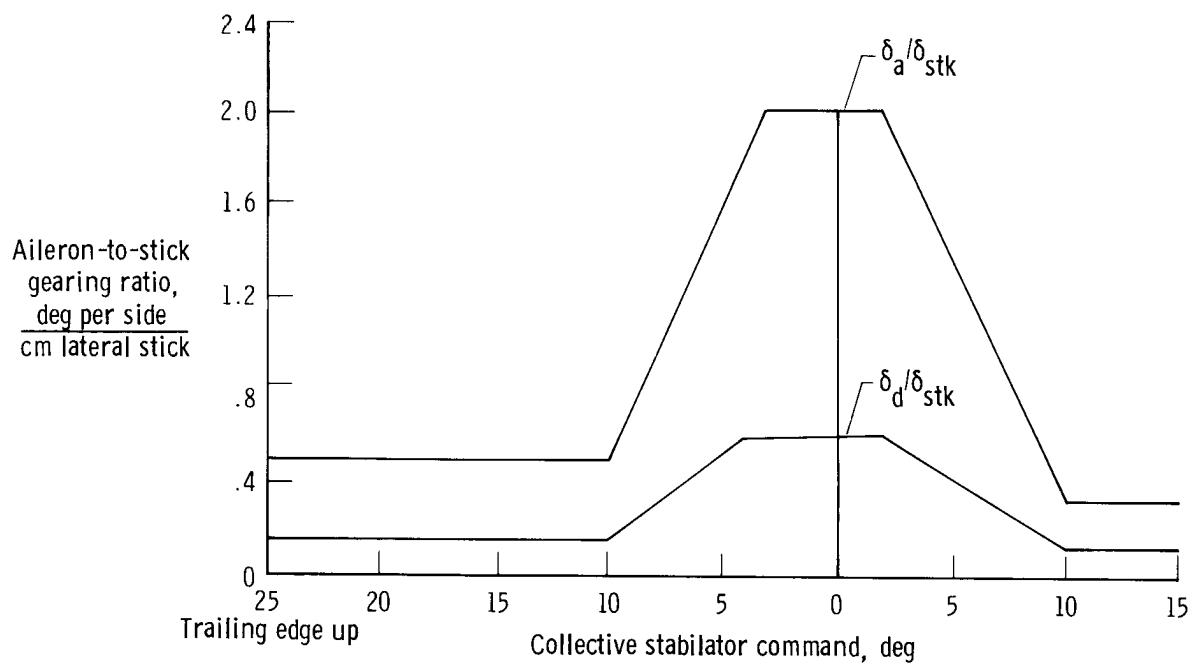


Figure 20. Roll ratio changer mechanical control authority (ref. 4). Gearing ratio is 2.0 with gear down regardless of mechanical stabilator command.

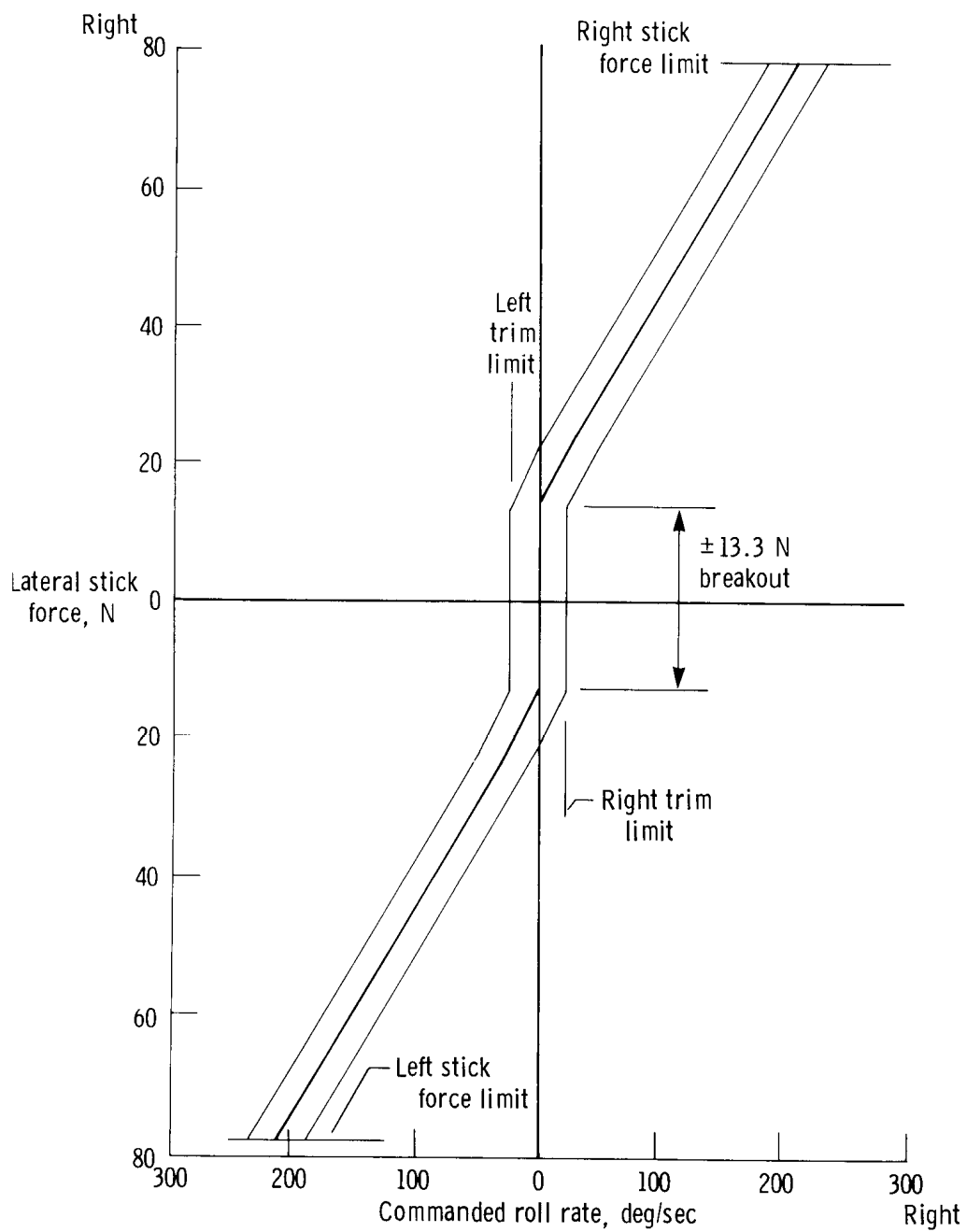


Figure 21. Roll CAS feel characteristics (ref. 4).

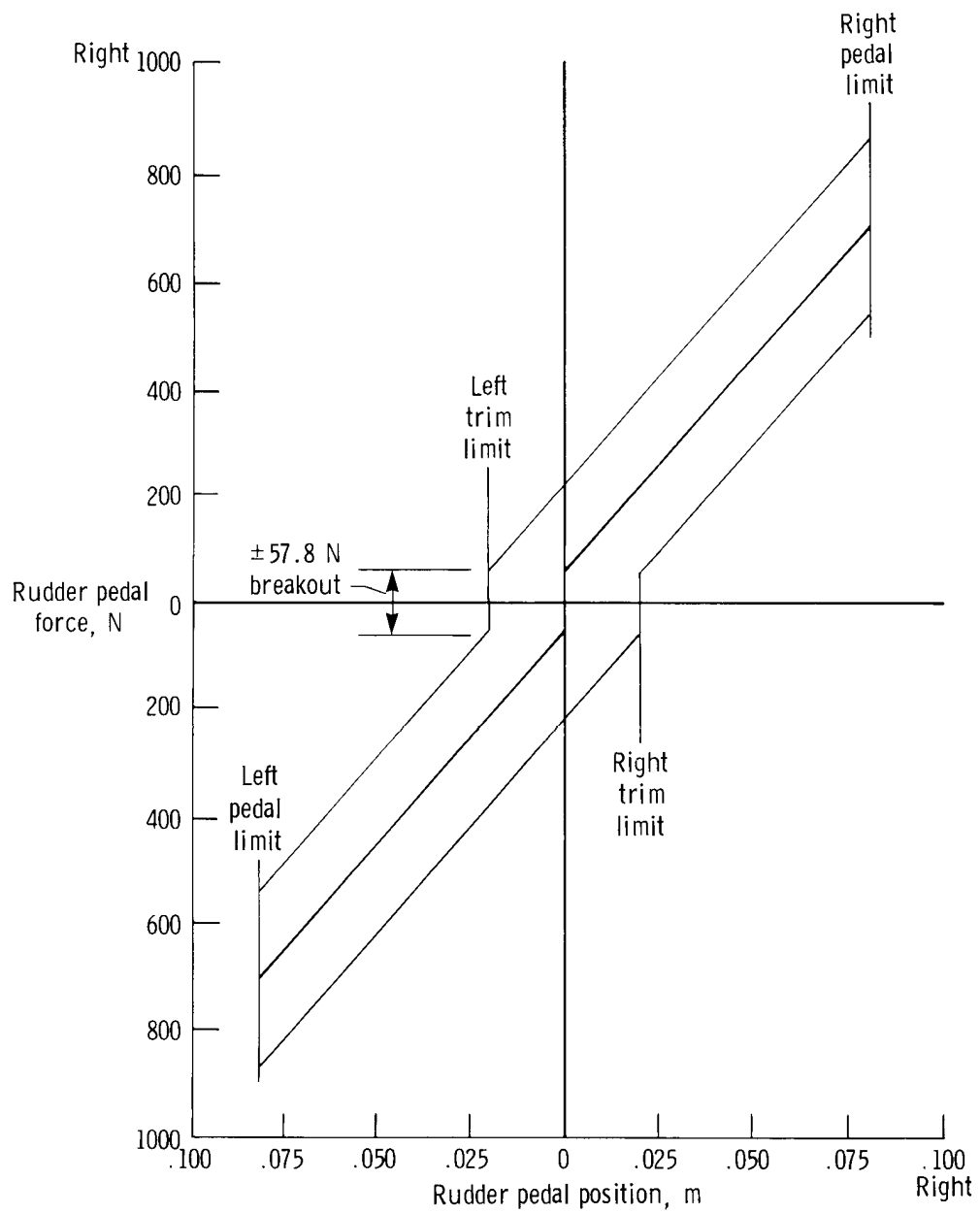


Figure 22. Rudder pedal force characteristics (ref. 4).

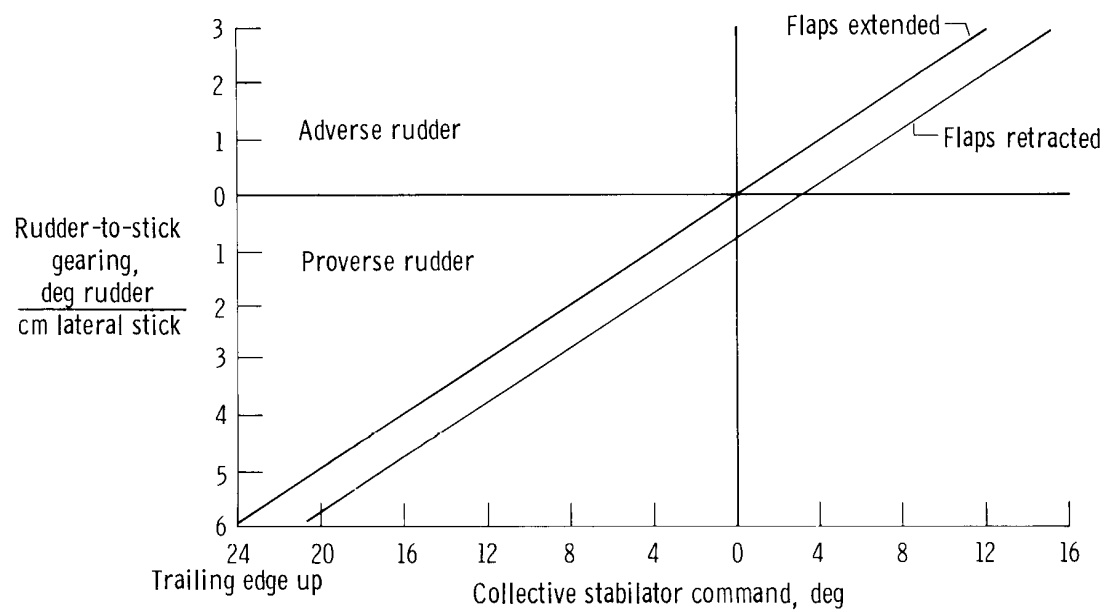


Figure 23. ARI schedule (ref. 4).

